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9. ABSTRACT

Groundwater quality in different parts of Pakistan is highly variable. According to one estimate 36 percent of the area considered arable is underlain with saline water not suitable for irrigation. However, there is a thin fresh water aquifer overlaying this saline water zone. Deep pumping is not possible in this area. A suggestion has been made that fresh water be covered by installation of low capacity skimming tubewells. Another suggestion is the direct utilization of groundwater by plants by installing open or closed subsurface drainage system and stabilizing the water table at a specific depth. Under the latter situation the plants would meet a small part of their requirements from surface irrigation, but a major part from the groundwater reservoir.

With this background a review of studies was made to gain knowledge concerning the zone of water uptake so as to estimate the contribution of groundwater available to plants. This knowledge was also sought to provide an indication of the zone of salt contribution and of nutrient uptake.

Research carried out revealed that under a constant boundary condition in which the water table is maintained at a fixed shallow depth, it was possible to predict the zone of water uptake. Experimental data agreed with predicted planes of water uptake.

Soil water evaporation data indicated ca.90% evaporation took place within the upper 150cm. This loss could be avoided by growing suitable crops and keeping the water table at a constant shallow depth. At shallow water table, data showed that irrigations were reduced and that such areas could possibly have an altered water allowance.

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PLANT UPTAKE OF WATER FROM A WATER TABLE

by Chaudhry
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Fort Collins, Colorado
March, 1975

WATER MANAGEMENT
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PLANT UPTAKE OF WATER FROM A WATER TABLE

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ABSTRACT

PLANT UPTAKE OF WATER FROM A WATER TABLE

Groundwater quality in different parts of Pakistan is highly variable. According to one estimate 36 percent of the area of culturable commanded land is underlain with saline water not suitable for irrigation. However, there is [redacted]hin [redacted]ui[redacted]. Deep pumping is not poss[redacted] has been made that the fresh water be covered by installation of low capacity skimming tubewells. Another suggestion is the direct utilization of groundwater by plants by installing open or closed subsurface drainage system and stabilizing the water table at a specific depth. Under the latter situation the plants would meet a small part of their requirements for surface irrigation but a major part from the groundwater reservoir.

With this background a review of studies was made to gain knowledge concerning the zone of water uptake so as to estimate the contribution of the groundwater available to plants. This knowledge was also sought to provide an indication of the zone of salt concentration and of nutrient uptake.

Researches carried out in this connection revealed that under a constant boundary condition in which the water table is maintained at a fixed shallow depth, it was possible to

predict the zone of water uptake. The experimental data agreed well with the predicted plane of water uptake.

Soil water evaporation data indicated that nearly 90 percent evaporation took place within the upper 150 cm. This loss could be avoided by growing suitable crops and keeping the water table at a constant shallow depth. Both the plane of uptake and evaporation data should help in locating the suitable water table depth.

At shallow water table, the data showed the irrigations were reduced substantially and accordingly such areas could possibly have an altered water allowance.

A need to undertake research in Pakistan on problems of water uptake, pattern of water use and the contribution of the ground water available to plants has been highlighted.

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I. INTRODUCTION

Rising water tables and soil salinization are among the major limiting factors of agricultural productivity in Pakistan. Investigations (1) carried out with the assistance of the U.S. Agency for International Development have inventoried the water and soil resources of the country and investigated the relations between irrigation activities, the natural hydrologic factors and the incidence of waterlogging and subsurface drainage problems. The findings are that most of the Indus plain is underlain by unconsolidated alluvium, which is saturated to within a few feet of land surface and there is a sizeable groundwater reservoir of enormous economic value. It has been recognized that the scientific management of this groundwater reservoir is the key to permanent irrigation agriculture in Pakistan.

The groundwater quality in different parts of Pakistan is highly variable. According to an evaluation made by the World Bank Consultants (2), out of an area of about 30 million acres of culturable commanded land in Pakistan nearly 48 percent is underlain with good quality water. Another 16 percent can be used after proper mixing, leaving a balance of 36 percent where the water is saline and not suitable for irrigation. An extensive program of pumping groundwater to recover the recharge is in progress in areas where the water is either of useable quality or it can be rendered fit after proper dilution. The saline groundwater areas which have a thin fresh water aquifer overlying saline water are not included in these programs. These areas constitute about 25 percent in the Punjab and 80 percent in the Sind provinces of the country. The amount of good quality re-charge into these saline pockets is tremendous--about 8MAF for Punjab and 14MAF for Sind. Suggestions (3) have been made to recover the fresh water by installation of low ca-pacity skimming tubewells or compound tubewells possessing single or multiple strainers in the saline water zones. So far, however, such tubewells have not been installed. An-other suggestion has been made to install either open or closed subsurface drainage systems and stabilize the water table at a specific depth and take advantage of its proxim-ity to the surface by reducing the irrigation requirements. Under such situations the plants will either require no sur-face irrigations or will meet a part of their requirements from surface irrigation supplies and a part from the ground-water reservoir. The effluent could be disposed of suitably. With passage of time it could be possible to leach out salts completely and to build a fresh water zone.

II. OBJECTIVES

Keeping this background of the groundwater hydrology of Pakistan in mind, an analysis and review of the studies carried out in this connection has been made with the following objectives:

1. To gain knowledge concerning the zone of water uptake so as to estimate and assess the contribution of the groundwater available to plants.
2. To help plan irrigation systems and fix water allowance and water duties consistent with the needs of the crop in shallow water table areas.
3. Irrigated agricultural land in arid regions with a shallow water table generally have associated salinity problems. A knowledge of the zone of water uptake should provide indication of the zone of salt concentration within the soil profile. What should be the optimum depth to water table both from the point of view of plants being benefited and control on salt movement under such situations?
4. The zone of water uptake may be the principal zone of nutrient uptake by plant roots. This is an important factor in considering fertilization practices. Furthermore when taking soil samples for fertility assessments consideration could be given to the zone of water uptake.

In areas where subirrigation is contemplated it would be necessary to know the depth at which the water table should be stabilized. There is a need to estimate the reductions in irrigation requirements for affecting economy in the use of water in areas with fluctuating water tables. The consumptive use study presently going on in Pakistan under the PL 480 program can be integrated with this program. The consumptive use study will among other things fix water allowance and water duties in deep water table areas (10 feet or beyond). A knowledge of water uptake in shallower water zones would indicate new patterns of water use and water duties.

It is hoped that with the above information the good quality fresh water in a saline area could be profitably used for agricultural production.

III. REVIEW OF LITERATURE

A. Water Movement in Soils

The availability of soil moisture, its uptake by the plant, its translocation through the plant and its evaporation into the atmosphere are various steps in the transfer of water through the soil-plant-atmosphere system.

Within the soil, water is involved in many different processes. Some processes seem to be almost purely physical while others seem to be predominantly chemical in nature, and still others appear to involve both simultaneously. According to Day, Bolt and Anderson (4), the formulation of a comprehensive theory which encompasses such diverse phenomena as soil water movement, water uptake by plants and water interaction with plant nutrients is difficult.

Experimental and theoretical work directed toward achieving a satisfactory understanding of soil water in its various forms and roles has been carried out actively for more than 65 years. Empirical measurements and qualitative interpretations have given way gradually to studies of fundamental mechanisms and to methods of expressing soil water phenomena mathematically. In modern perspective quantitative measurements and mathematical expressions are essential to the understanding of soil water and to the application of the knowledge to practical agriculture.

The forces acting on the soil water can be classified for convenience into (i) matric forces (those which result from the presence of the solid phase), (ii) osmotic forces (those caused by dissolved solutes), and (iii) body forces (inertial forces and gravitational forces).

According to Miller and Klute (5) water movement in the soil comprises three phases: (i) infiltration, (ii) redistribution and (iii) withdrawal.

Infiltration

The infiltration phase occurs primarily while the water is being applied. Water is subject to forces of gravity, adhesion and cohesion. At first water moves downwards, fairly rapidly under gravitational force, filling all the pore spaces and saturating the soil to a depth which depends on the amount of water applied and on specific soil characteristics.

The rate of infiltration into the surface and the rate of flow and advance of a wetting front within the soil depend primarily upon the porosity characteristics and the nature of the mineral and organic substances forming the solid phase of the soil. If particle surfaces do not wet readily, as is possible when certain kinds of organic residues are present, infiltration can be seriously retarded. If particle surfaces wet easily, the resulting flow is to a large degree dependent upon the size and distribution of the pores--including, particularly, whatever stratification may exist.

Redistribution

During the redistribution phase water achieves an equilibrium. About 24 to 72 hours after the irrigation application the downward moisture movement becomes negligible and drainage essentially ceases. The moisture content at this stage is called "field capacity." Field capacity is defined as the moisture content of a deep, permeable, well drained soil several days after wetting. At field capacity, there is a fairly distinct boundary between the wetted part of the soil and the dry soil underneath. However, it is pointed out that the above applies only to a well-drained soil. When an impermeable layer is present near the soil surface or the groundwater table is high, the root zone may remain water-logged for long periods. Another factor affecting the precision of the field capacity concept is extraction of water by the growing crop, during the period of time between the application of water and the attainment of field capacity in the soil. Water uptake by plant affects the rate of downward flow and the losses beyond the root zone and cannot be considered as negligible influence within reasonable times after irrigation (6).

Withdrawal

Withdrawal consists of transpiration, affecting the entire root zone and evaporation occurring at the soil surface. The withdrawal continues, until the wilting point or permanent wilting percentage is reached. The amount of water held in the soil between field capacity and wilting point is generally considered to represent the reservoir of water available for plant use. A certain amount of water, however, may be taken up by plants from soils with water contents above field capacity and below wilting point. The capacity of the reservoir of available water depends on the depth of soil, its texture and structure. For each crop it will depend on the depth and extent of the rooting system. Other factors affecting water removal by plants include the genetic characteristics of the plant, the presence or absence of hard pans, drainage characteristics, the presence of toxic substances and availability of plant nutrients. The quantity of water in the soil at which plants begin to suffer depends upon water conduction properties of the soil, upon the salinity status and upon external environmental factors.

Vapor Movement

Water also moves through unsaturated soils by vapor transfer. As a result of temperature gradient, the water movement is from warm to cold areas. Under natural conditions soil air is always saturated with water vapor, except in the uppermost zone of the soil. Below a depth of 5 to 10 cm the vapor pressure is generally greater than that of the atmosphere (7). During the day much of the solar energy is absorbed by a shallow layer of soil which becomes warmer than the atmosphere above and the underlying soil layers. As a result, water vapor will move upwards from the surface layer into the atmosphere (evaporation) and downwards into the colder, dry layers where the moisture condenses. At night the opposite process occurs. Vapor moves from the lower layers and condenses near the still colder soil surface. It has been stated that whereas water in the liquid form may amount to 30 percent or more of the weight of the soil, the weight of water vapor is rarely in excess of 5ppm of soil weight (4). Generally, the main effect of vapor movement is to contribute to the loss of water through evaporation from the soil because the water vapor pressure in the soil atmosphere is generally greater than that of the atmosphere above the soil. Losses by evaporation usually are confined to the surface few centimeters of the soil. Vapor losses from layers deeper than 15 to 20 cm are usually negligible (8).

Soil Water Forces and Their Measurement

Water plays a vital role in many soil processes. It functions as a solvent, as a leaching agent, as a reactant, as a medium for chemical reactions and as a plasticizing agent. The presence of water in the soil in its various stages of wetting has been described functionally in terms of hygroscopic, capillary and gravitational water. These types are based on the three modes of water movement, vapor, capillary and gravity flow. More recently it has been found that there are functional relationships between the water content and physical variables, such as vapor pressure, matric suction and capillary or hydraulic conductivity. These functions are essentially continuous, showing that there are no sharp distinctions between the different stages of wetting. Thus, the older terms have been found to be too arbitrary for quantitative usage.

Energy State of Soil Water

The energy of the soil water is usually measured in reference to a flat surface of pure water at some specified elevation and at a standard pressure. Pure water in a saturated soil at the same elevation, pressure and temperature as the references has a total water potential of zero. As defined by the Soil Physics Committee on Terminology for the International Society of Soil Science in 1963, the total potential of soil water is "the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water (at the point under consideration)" (9). As the soil dries out, the remaining water is more tightly held. Since energy must be added to this soil water to restore it to the reference state, its potential energy is considered to be negative. Similarly, the water potential of a soil at a lower elevation than the reference is negative. If it is higher than the reference level, its water potential can be positive. The same holds true for samples at different pressures than the reference. Solutes in the soil water also lower its potential energy.

The total water potential, Ψ, can be divided into four component potentials. These are (i) the matric potential (Ψ_m) which results from the interaction of soil particle surfaces with water, (ii) the osmotic potential (Ψ_w) which results from the solutes dissolved in the soil water,

(iii) the gravitational potential (Ψ_z) which results from elevation with respect to the reference level and (iv) the pressure potential (Ψ_p) which results from external pressure on the soil water.

In unsaturated soils the pressure potential usually is considered zero and in saturated soils the matric potential usually is considered zero. When dealing with the movement of liquid water in unsaturated soil, usually it is necessary to consider only the matric and gravitational components of the water potential. In this case the term soil water tension has traditionally been used instead of matric suction.

Any unit of pressure may be used to express the tension or suction of a sample of soil. Following are some commonly used pressure units which are equivalent at 21°C.

1	atmosphere
1.013	bars
101300	dynes per square centimeter
14.71	pounds per square inch
1036	centimeters of water
34.01	feet of water
76.39	centimeters of mercury

Water Content of Soils and Its Measurement

According to Corey, Slatyer and Kemper (10) the water content of soils is usually expressed as a ratio or percentage in one of the three ways, the quantity measured being dimensionless in each case:

1. Volume water content--the amount of water lost from the soil on drying at 105 to 110C expressed as the volume of water per bulk volume of soil (Intl. Soc. Soil Sci. 1963).

2. Water content on dry weight basis--the amount of water lost from the soil on drying at 105 to 110C expressed as the weight (or mass) of water per weight (or mass) of dry soil (Intl. Soc. Soil Sci. 1963).

3. Saturation--the amount of solution contained in the soil expressed as the volume of solution per volume of soil pore space (11). This should not be confused with the term saturated which means all of the pore space is occupied with liquid.

Various procedures have been used in measuring the amount of water in the soil. These are:

1. Oven drying. It is the most basic and precise method of measuring soil water content. The definition of soil water content involves the loss of weight of a soil sample when it is dried in an oven at 105 to 110C until it reaches constant weight.

2. Chemical drying. Employs the use of calcium carbide in a small pressure cell and measures the pressure developed from the formation of acetylene gas.

$$H_2O + CaC_2 \longrightarrow C_2H_2\uparrow + CaO$$

3. Neutron Scatter. This is a modern practical method of measuring soil water content which involves the use of

high energy neutrons and measures the degree to which they are slowed down or "thermalized" in the soil. The neutron scatter method determines water content on a volume basis.

4. Gamma-Ray Attenuation. This measures moisture status in situ by the absorption of gamma rays, without disturbance of the system.

Measuring Soil Water Potential

Various methods and types of equipment have been developed to measure the energy relationships of soil water. A simple and very commonly used method of evaluating the matric potential (soil water tension or suction) is through the use of "tensiometer." The tensiometer is a device consisting of a porous cup connected through a rigid system to a pressure gage capable of registering pressure values between zero and that of the atmosphere. Another practical and extensively used method of measuring soil water matric suction involves the use of electrical resistance blocks. The best known resistance units are the "gypsum blocks," often referred to as "Bouyoucos blocks." The electric resistance of these blocks is calibrated against matric potential.

Curves of soil water content versus water potential are useful in characterizing different soils. Such curves are shown in Figs. 1 and 2 (12). Fig. 1 represents a desorption curve. A vertical section in the curve represents a situation where a soil contains a large number of pores of a particular size. When a tension is reached at which these pores can empty, tension changes little until the pores are

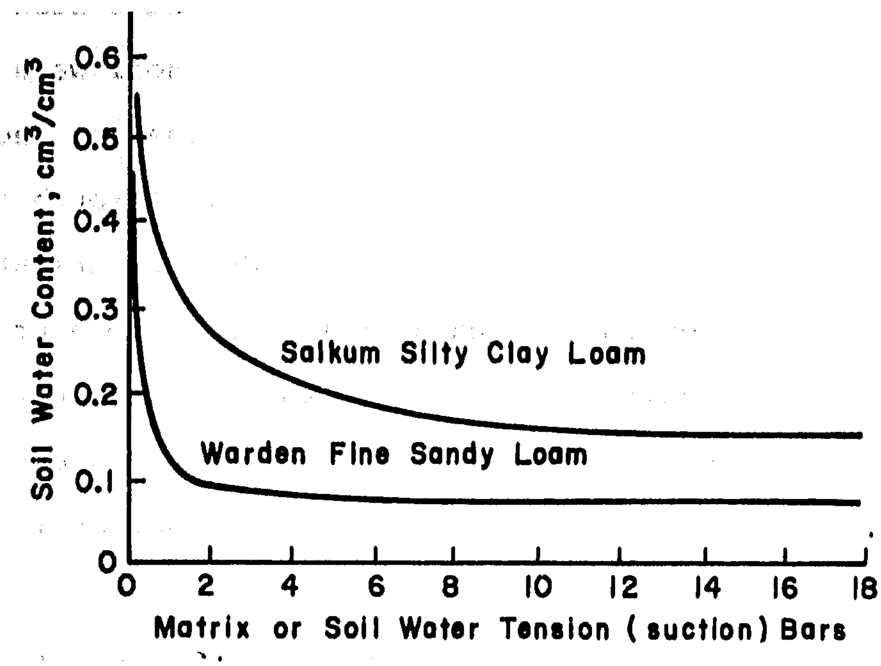


Fig. 1. Typical desorption curves (i.e. where equilibrium is approached from the wet side) for soils of two textural classes (12).

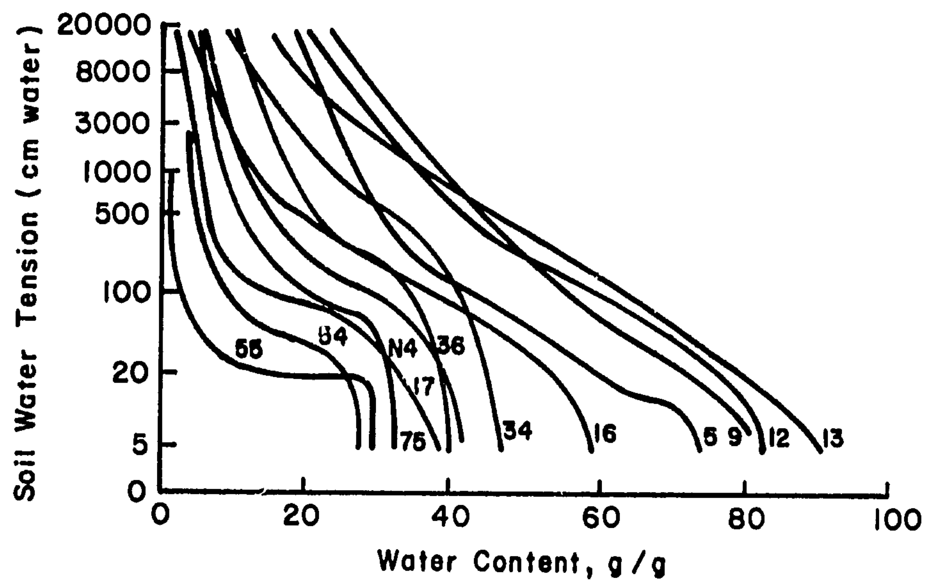


Fig. 2. Soil water tension as a function of water content for the following soils. (U.S. Salinity Lab data)

55 Screened sand
54 Ramona sand
75 Indio loam
17 Placentia clay loam
N4 Greenfield loam
36 Hanford fine sandy loam
34 Fresno loam
16 Yolo clay loam
5 Antioch clay
9 Olympic clay
12 Chino silty clay
13 Chino silty clay loam

all empty so that a large water content change occurs with an extremely small tension change. A horizontal section in the curve represents a situation where no pores are available of a size that can drain over the tension range concerned. Straight line sections at intermediate slopes represent the situation where pore size distribution results in uniform release of water per unit tension change. Thus the shape of the desorption curve is indicative of the pore size and pore size distribution in a soil.

The agricultural use and value of a soil are affected greatly by soil properties indicated by the desorption curve. It is evident that water available for plant use at different soil water tensions varies greatly with the soil. The number of days remaining before the soil will reach the wilting point, starting with any given soil water concentration or corresponding tension is shown on the ordinate in Fig. 1.

The coarse-textured soils are observed to release water rapidly over the low tension range, whereas the fine-textured soil releases water more gradually over the high tension range.

B. <u>Unsaturated Flow Upward in the Presence of Water Table Theoretical Considerations</u>

In recent times a number of reviews have appeared on the theory of transport of soil water. The importance of water in plant growth has prompted the study of the mechanism of soil water uptake by plants. A large fraction of the water that falls on the surface of the soil as rain or irrigation moves into and through the soil during the processes of infiltration, drainage, evaporation, redistribution within the soil, and water uptake by plant roots. A major part of all of these phenomena involves flow of water in unsaturated soil.

An unsaturated soil consists of three phases, viz. a solid phase, a solution phase and a gaseous phase. According to Klute (13) the movement and retention of water in unsaturated porous media may be approached from (i) the molecular (ii) the microscropic or (iii) the macroscopic viewpoint. In the molecular point of view one devises theories and explanations of the mechanisms of flow and retension in terms of the behavior of the water molecules. Statistical mechanical concepts might be used. At an intermediate level, the microscopic, one may develop a theory of flow treating the fluid in the pores as a continuum and applying the principles of continuum mechanics, especially fluid mechanics, to work out the detailed behavior of the fluid within the pores. As an example of this approach one might apply the Stokes-Navier equation for the flow of a viscous fluid to work out the detailed fluid velocity pattern within the pores. The complicated pore geometry and consequent impossibility of specifying the boundary conditions on the flow, preclude any practical progress by this approach, except in the case of rather simple pore space geometry, such as flow in straight capillary tubes, or between parallel plates.

In either case (i.e. molecular or microscopic) one must proceed in the development of flow theory to the macroscopic level. We cannot observe the behavior of individual molecules, nor can we observe the velocity and fluid pressure distributions that one might in principle calculate in the microscopic approach. A macroscopic theory of flow is needed.

In the macroscopic approach, all variables are assumed continuous functions of space and time, with derivatives of as high an order as may be needed. The porous medium is treated as a superposition of three continuous phases, solid, solution and gas. Velocities, pressures and other necessary variables are treated as point functions.

The macroscopic point of view of soil water flow as per Klute (14) is composed of six contributions: (i) the bulk, convective transport of solution phase relative to the solid phase, (ii) the bulk convective transport of the gas phase, relative to the solid phase, (iii) diffusion and dispersion in the solution phase, (iv) diffusion and dispersion in the gas phase, (v) convective transport of the water in the solution phase due to the motion of the solid phase, and (vi) convective transport of the water in the gas phase due to the motion of the solid phase. If the solid phase acts in a rigid manner, the last two contributions may be ignored. The mechanical forces include gravity, the pressure gradient force, and (in the case of the solution phase, at least) a contribution from adsorptive forces.

The mathematical physical approach to the analysis and description of soil water flow on the macroscopic level involves (i) the selection of relations between the components of the mass flux of water and the appropriate driving forces, and (ii) the combination of these flux equations with the mass balance equation for water.

Soil Water Flow Equation

Whisler, Klute and Millington (15) have analyzed and developed a model of soil water flow in one dimensional form on a macroscopic level. In this analysis it has been assumed that the modified Darcy equation for flow in an unsaturated soil is valid. viz

$$v = -K(h)\nabla H \qquad [1]$$

where v is the volume flux i.e., the volume of water passing through unit cross-sectional area of soil in unit time, ∇H is the gradient of the hydraulic head H, and K(h) is the conductivity of the soil as a function of the pressure head h. The hydraulic head is considered to be the sum of a gravitational and pressure heads, both expressed in length units. When the conservation of matter principle is imposed, the equation for vertical flow is:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial v}{\partial z} + s \qquad [2]$$

where θ is the volumetric water content, t is the time, v is the soil water flux in the z direction (z is positive downward) and s is the source term that represents water uptake by plant roots. The source term is the volume of water extracted from a unit volume of soil per unit time.

Equations [1] and [2] can be combined to give the equation for vertical flow of soil water.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z}\right) + \frac{\partial K(h)}{\partial z} + s \qquad [3]$$

where θ is the volumetric water content

t is the time

z is the length in the vertical direction chosen such that z is positive upward

h is the pressure head also with dimension of length

$K(h)$ is the hydraulic conductivity of the soil as a function of the pressure head h expressed as length per unit time and

s is the source term expressed as volume of water produced per unit volume of soil per unit time.

The extraction of water from the soil by plant roots can be represented by a negative function i.e. s is negative.

Evaluation of Water Withdrawal/Uptake

The determination of water withdrawal/uptake is done by evaluation of the source term. The source term s is determined either by using the soil water flow equation [3] involving use of soil parameters or by modelling technique involving use of plant parameters.

1. Water Withdrawal Involving Soil Parameters

The source term s can be calculated from the soil water flow equation [3], if the change in water distribution with time can be measured and water flux can be calculated from measured values of h. Both the differential and integral forms of equations are used.

a. Differential Forms of Equation

When the vertical flux is equal to zero, equation [3] becomes

$$s = \frac{\partial \theta}{\partial t} \qquad [4]$$

Here the only necessary measurement is the soil water content as a function of depth and time. Where zero flux is assumed equation [4] can be used to calculate the source term. This assumption, however, has introduced many errors especially where frequent irrigation is applied.

Under a steady state condition equation [3] becomes

$$s = -\frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z}\right) - \frac{\partial K(h)}{\partial z} \qquad [5]$$

This situation is applicable, when plants are growing in soil with water table at a fixed depth and the water in the soil is at steady state.

Under nonsteady state with nonzero flux, the form of soil water flow equation is

$$s = \frac{\partial \theta}{\partial t} - \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z}\right) - \frac{\partial K(h)}{\partial z} \qquad [6]$$

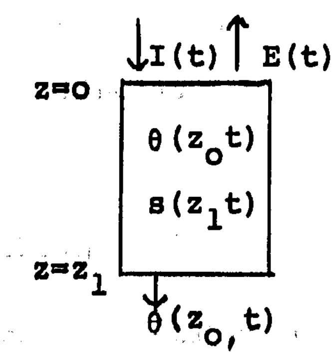
b. <u>Integral Forms of Equation</u>

Rose and Stern (16) have presented an integral form of soil water flow equation [3] which is as below

$$\int_{t_1}^{t_2} (I-v_z-E)\,dt - \int_{o}^{z}\int_{t_1}^{t_2} \frac{\partial\theta}{\partial t}\,dzdt = \bar{R}_z \qquad [7]$$

Where I is the rate of water supply, E is the evaporation rate from the soil surface, v_z is the verticle flux of water in the soil at depth z, $\bar{R}_z$ is a time average value of R_z, the rate at which water has been withdrawn by roots from the soil surface down to depth z. R_z can be written as $R_z = \int_o^z s_z d_z$. s_z is determined by differentiating $\bar{R}_z$ with respect to z.

The derivation of equation [7] can be approached as follows (17)



Consider a time interval $\Delta t = t_2-t_1$. Water fluxes in the soil is assumed to take place in the vertical direction only. Consider a volume of soil bearing vegetation with an upper boundary at the soil surface (depth $z = o$), a lower boundary at depth z and of unit cross sectional area in the horizontal plane.

Assuming constant density for water a volume balance for the soil depth Δz and time interval Δt can be written

volume in Δt	-	volume out in Δt	=	volume increase in soil water storage in Δt and depth Δz	+	volume withdrawn in time Δt and depth Δz
(1)	-	(2)	=	(3)	+	(4)

(1) <u>volume in Δt</u> $= \int_{\Delta t} [I(t) - E(t)]dt$

where

$I(t)$ = volume of water/land area/time applied as irrigation

$E(t)$ = volume of water/land area/time removed by evaporation

(2) <u>volume out in Δt</u> $= \int_{\Delta t} \theta(z_1,t)dt$

where

$\theta(z_1,t)$ = volume flux of water/area/time at length z_1.

(3) <u>volume increase in storage</u>

volume stored in depth Δz = $\int_{\Delta z} \theta(z_1 t)dz = v_{\Delta z}(t)$

Time rate of change of storage in depth Δz

$$\frac{d}{dt}(v_{\Delta z}(t)) = \frac{d}{dt}\int_{\Delta z} \theta(z,t)dz = \int_{\Delta z} \frac{\partial\theta}{\partial t}dz$$

volume increase in storage in Δt and Δz =

$$\int_{\Delta t} \frac{d}{dt} V_{\Delta z}(t)dt = \int_{\Delta t}\int_{\Delta z} \frac{\partial\theta}{\partial t}\, dzdt$$

(4) <u>volume withdrawn from depth</u> Δz in Δt

Define $\bar{s}(z) = \frac{1}{\Delta t}\int_{\Delta t} s(z,t)dt$ time average rate of production of water at any depth z for the time interval Δt.

then $-\int_{\Delta z} \bar{s}(z)dz = \bar{W}_{\Delta z}$ time rate of water removal for depth Δz, and

$\bar{R}_{\Delta z} = \Delta t \bar{W}_{\Delta z}$ = amount (volume) of water removed from depth Δz in time Δt.

$$\bar{R}_{\Delta z} = \Delta t[-\int_{\Delta z} \bar{s}(z)dz]$$

$$= -\Delta t[\int_{\Delta z} \frac{1}{\Delta t} \int_{\Delta t} s(z,t)dtdz]$$

$$= -\int_{\Delta z}\int_{\Delta t} s(z,t)dtdz$$

The volume balance equation can now be written as

$$\int_{\Delta t} [I(t) - E(t)]dt - \int_{\Delta t} \theta(z_1,t) = \int_{\Delta t}\int_{\Delta z} \frac{\partial t}{\partial z} dzdt + \bar{R}\Delta z$$

or

$$\bar{R}_{\Delta z} = \int_{\Delta t} [I(t) - \theta(z_1,t) - E(t)]dt - \int_{\Delta t}\int_{\Delta z} \frac{\partial t}{\partial z}dzdt$$

When the water table is maintained at a fixed elevation it is difficult to estimate $\frac{\partial h}{\partial z}$ near the water table because the gradient is very small. Also there is the uncertainty of the water content vs suction relationship near saturation. In this case, the soil water flux below the root zone can be calculated from the rate of water supply to the water table as shown by Reicosky et al.(18).

$$\int_{z_1}^{z_2}\int_{t_1}^{t_2} \frac{\partial \theta}{\partial t} dzdt = \bar{v}(z_2) - \bar{v}(z_1) \qquad [8]$$

where $\bar{v} = \frac{1}{t_2-t_1} \int_{t_1}^{t_2} [K(h)\frac{\partial h}{\partial z} + K(h)]dt$

$\bar{v}(z_1)$ is the time averaged flux calculated as the average of rate of inflow from the water table at time t_1 and t_2 and

$\bar{v}(z_2)$ is the time averaged flux at position z_2 which may be obtained by using the equation [8].

2. Water Uptake By Modeling of Source Term

Basically two approaches have been made to study the water uptake by plant roots. This has been done by calculating the source term using either microscopic or macroscopic parameters.

Although the process of water uptake from the soil by plant roots occurs at the microscopic (single root) level, most of the parameters that can be measured relatively easily are macroscopic. Several models have been presented to describe the source term on a macroscopic level. Gardner (19), Whisler et al. (15) and Nimah and Hanks (20) have used similar ideas in developing the model.

Whisler et al. proposed the following model for the source term and evaluated its effect on the soil water flow system.

$$S = A(z)K(h)(h_p - h) \qquad [9]$$

where $A(z)$ is the product of the root length per unit volume of soil

$K(h)$ is the soil hydraulic conductivity

h_p is the pressure head of the water in the plant roots, and

h is the pressure head in the soil.

This model is essentially the same as presented earlier by Gardner (19). Nimah and Hanks (20) modified equation [9] by including the osmotic potential of the soil water in the term h and correcting the term h_p to account for both gravity and friction loss in the roots. Molz and Remson (21) presented the source term as a product of soil diffusivity, a quantity which they called "the effective root density" and a constant which contained the transpiration rate.

The limitations of above models are that the pressure head h at a point on the macro level is considered to be volumetric average of the microscopic distribution of h in the soil pores. If uptake is occurring, the pressure head in the vicinity of the roots will tend to be lower than the pressure head on the macro level. As a consequence thereof, the plant roots are exposed to a soil water pressure head that is less than the macroscopic average pressure head. The pressure head of the water in the plant roots is difficult to measure directly. Instead the pressure is measured in leaves or stems. The parameter K(h) is a function of h on macro level and does not necessarily represent the hydraulic conductivity near the root. If roots contract with increased plant water stress the interfacial resistance to flow will restrict the flow of water from the soil to the roots. The parameter A(z) should represent the effective roots, i.e. those roots that are physiologically capable of taking part in water uptake. The problem is in measuring the effective roots. Osmotic effect is another limitation of the model. This effect may not be complete, but some observable effects are there due to leaky nature of the plant membranes.

Mechanism of Water Uptake By Plants

Water movement in relation to plant growth involves three phases: water uptake by the plant, water movement through the plant and transpiration by the plant.

As water is generally free to move across the plant-soil soil-atmosphere, and plant-atmosphere interfaces, Philip (21) stresses the importance of considering the water transfer system in the soil-plant-atmosphere continuum as a whole.

Cultivated plants absorb water from the soil mainly through their roots and root hairs. The root system of most crop plants present an enormous surface area that is active in water absorption from the soil. Good aeration is essential for maximum water absorption. The reason seems to be that a good oxygen supply is required for the maintenance of the respirational activity and permeability of the roots; and these factors are, in turn, essential for the active and passive absorption of water (22).

Passive Absorption

Most of the water taken up by plants merely passes through the plant and is eventually lost because of transpiration, which occurs largely from leaf cells. The plant performs no active function in the process except to provide the channel through which the water moves from the soil to the atmosphere and consequently this process is frequently called passive absorption. As evaporation takes place from the leaves there is a general lowering in the water potential of the leaves and the resulting potential gradient is the driving force of the passive absorption of water from the soil. Water then moves from the soil surrounding the roots, along the water potential gradient, through the plant, and so into the atmosphere. Passive absorption requires good permeability which, in turn, requires adequate aeration.

Active Absorption

Sometimes water rises in plants even though transpiration is negligible or zero. Under these conditions, respiration in the plant roots produces energy that pushes water up from the roots. This is the action that causes plants to exude water from a cut stem. Exudation of water may take place against considerable pressure. The amount of water that moves this way is generally small and can account for only a small fraction of the water usually taken up by plants, but it would be sufficient to supply all plant needs if transpiration were eliminated (23). Because this positive push of water depends upon the respirational activity of the roots, it is called active absorption. The uptake of water from the soil by the plant appears to be along a water potential gradient, but the detailed mechanism by which water is moved from the roots upward is not known. Because oxygen is required for root respiration, active water absorption is dependent on adequate aeration.

Under conditions of normal high temperatures the contribution of active absorption to the water supply of the crop is negligible, as compared with passive absorption, and is usually less than 10 percent of the total water absorption of the plant (23).

Aerial Absorption of Water

It has been found that certain plants growing in soils at wilting point are able to absorb moisture from the atmosphere. Similarly surface water on the leaves reduces transpiration somewhat, thereby reduces the water deficit and prolongs survival.

Aeration Effects

A sudden reduction of soil aeration will cause a growing plant to wilt because of a reduction in the rate of water absorption. If the soil air is suddenly replaced by carbon dioxide, both transpiration and exudation of water are reduced. Under natural field conditions oxygen deficiency is more serious in reducing absorption than is carbon dioxide accumulation. Oxygen deficiency reduces the respiration of the plant root and indirectly influences the root permeability. While a lack of oxygen may strongly inhibit active absorption, the water absorbed in this process amounts to such a small proportion of the total water uptake by plants that the effect of oxygen deficiency on permeability is probably more significant.

Water Use Pattern

According to Gardner (24) the pattern of water use in a root zone depends upon the root distribution, root permeability and upon the water retaining and transmitting properties of the soil. Gardner and Ehlig (25) stated that the passive absorption of water by plants takes place in response to differences in potential energy between the water in the plant and water in the soil. An equation which assumes that the rate of water uptake is proportional to the potential energy gradient and inversely proportional to the impedence to water movement within the soil and the plant was described. This is expressed as

$$q = \frac{\delta - \tau}{I} = \frac{\delta - \tau}{I_p + I_s} \qquad [10]$$

where q is the volume of water taken up in unit time by the plant per unit volume of soil

δ is the diffusion pressure deficit

τ is the soil suction

I is the impedence (sum of plant and soil impedence)

I_p is the plant impedence, and

I_s is the soil impedence

The potential energy is expressed in terms of diffusion pressure deficit and the soil suction. This equation is similar to the model of Whisler et al. (equation 9).

Experiments were conducted by Gardner and Ehlig (25) on trefoil, cotton, sorghum and pepper in a greenhouse in columns 14 cm in diameter and 133 cm deep filled with Pachappa sandy loam and kept at a water table depth of about 110 cm from the soil surface under steady state conditions. The soil water suction was measured with tensiometers spaced at 10 cm intervals to a depth of 90 cm from the soil surface. In addition resistance blocks were placed at several depths.

Steady state flow was approached from initially low suction and was achieved after two or three weeks. The water flux was calculated from the hydraulic gradient and the hydraulic conductivity of the soil. Flux is a specification of the amount of given entity passing through a unit cross sectional area of medium per unit time.

Results for trefoil are shown in Fig. 3. The solid line denotes the total flux determined by the rate of supply of water to the water table. The dotted line shows the soil flux calculated from the hydraulic gradient and the unsaturated conductivity of the soil. The unsaturated conductivity was not measured on the actual soils. On the other hand values were taken from an average curve obtained on separate samples by several methods. The slope of the soil flux line with respect to depth is a measure of the rate of uptake of water by the plant roots and it represents the change in flux with depth. Similar results obtained with pepper, cotton and sorghum are shown in Fig. 4. The water uptake was more nearly concentrated at a given depth for these three crops. The sorghum had the shallowest root system. For all species much of the water moved upward from the water table for 20 to 40 cm before entering the root system even though roots penetrated the bottom of each cylinder.

In the nonsteady state experiments of Gardner and Ehlig, the soil was initially wetted nearly to saturation and allowed to dry by transpiration. The water content as a function of depth was estimated from the soil suction and the

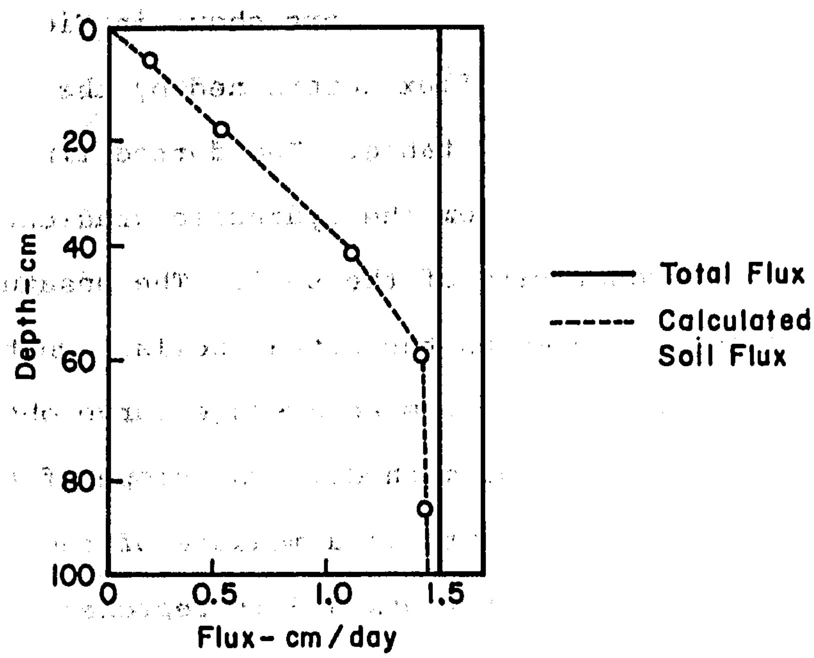


Fig. 3. Total upward flux of water and calculated flux in the soil under steady state conditions for Birdsfoot trefoil (24).

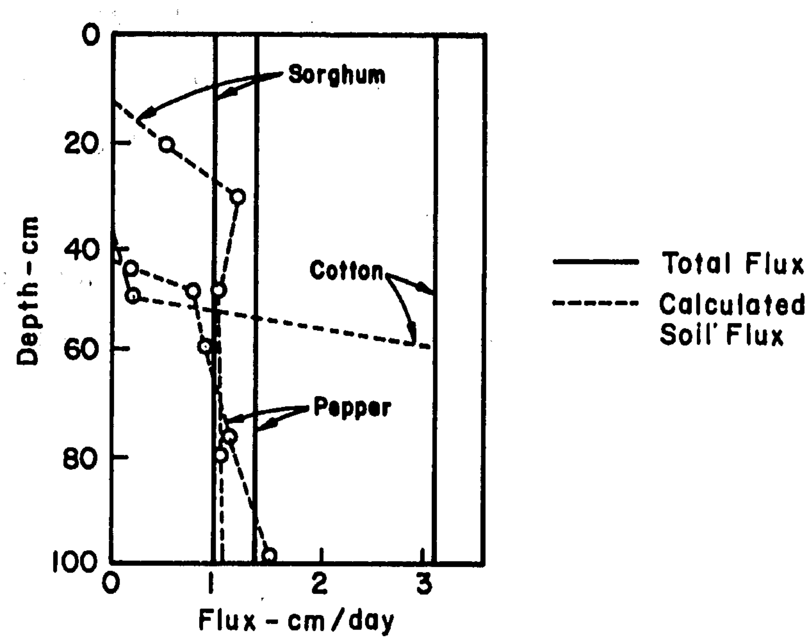


Fig. 4. Total upward flux of water and calculated flux in the soil under steady state conditions for three species (24).

relation between soil suction and water content obtained on soil samples from several depths in each column. The total flux of water at a given depth was calculated from the rate of water loss from below that depth. The upward flux of water in the soil itself was calculated from the hydraulic gradient and from the average unsaturated conductivity curve.

The results of both steady state and nonsteady state on pepper, cotton, trefoil and sorghum indicated that an appreciable fraction of the water below 60 cm from the surface moves upward through the soil rather than through the plant roots. The studies also indicate that water movement within the root zone cannot a priori be neglected even though the soil-water content may be below the traditional field capacity.

Reicosky et al. (18) have presented data on water uptake patterns of soybeans (Glycine max.) grown in soil columns 122 cm long and 10.2 cm in diameter filled with Dickinson sandy loam. A water table was maintained 100 cm from the soil surface. At selected times after planting, several soil columns were cut into 10 cm lengths and samples were taken for water content and root length measurements. The soil water flux was determined from the hydraulic gradient and the hydraulic conductivity of the soil using the continuity equation already referred to. The source term distribution with depth was also calculated.

Sink profiles which were used to infer water intake, were compared with root density profiles. It is pointed out here that sink is a term that represents water uptake by plant roots. The sink term is the volume of water extracted from a unit volume of soil per unit time. Water uptake in soil columns was analyzed using the flow equations for water movement in the soil, treating the root system as a macroscopic sink.

Examples of the soil water flux profiles for 59 and 73 days after planting are shown in Fig. 5. At 59 days after planting the soil water flux in the bottom of the column was about 11 cm/day and decreased sharply in the 50 to 70 cm depth increment. The sharp decrease in soil water flux in this zone was caused primarily by the dramatic change of hydraulic conductivity with depth as shown in Fig. 6. For example the hydraulic conductivity changed from 1.5 to 9.0×10^{-3} cm/day in going from the 80 to 90 cm depth increment to the 40 to 50 cm depth increment while the hydraulic gradient went from 0.8 to 11.0 cm/cm at the same depths. Although the hydraulic gradient did change in this region, the resulting soil water flux profile was primarily due to the decreasing hydraulic conductivity with decreasing water content (increasing suction). The low hydraulic conductivity above this region resulted in a very small soil water flux. The same trend was found in columns analyzed 73 days after planting.

The sink term was distributed throughout the upper portion of the columns in the early part of the experiment. In the latter part (at 59 days) the magnitude of the sink was

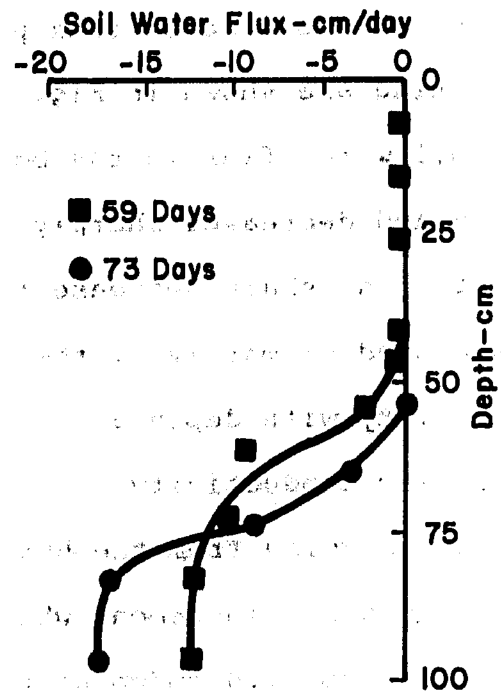


Fig. 5. Examples of the soil water flux profiles as a function of depth at 59 and 73 days after planting (18).

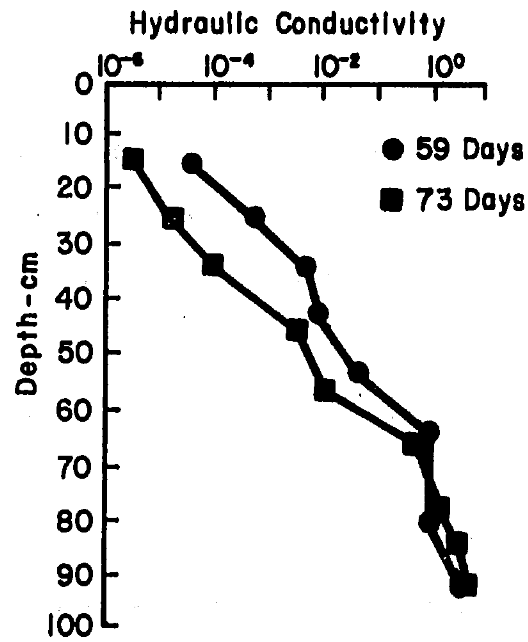


Fig. 6. Hydraulic conductivity vs. depth at 59 and 73 days after planting (18).

very small in the upper portion of the columns, reached a maximum in the 50 to 60 cm depth increment decreased at lower depth. The sink profile at 73 days after planting shows a similar trend, with the maximum sink in the 70 to 80 cm depth increment. These are shown in Fig. 7. The results indicate that in the latter part of the experiment maximum water absorption was occurring in the capillary fringe just above the water table. The maximum sink value increased with time, and tended to increase in depth with time. The increase in the sink term with time was related partly to an increase in root density in the same region and partly to an increase in the plant demand for water.

The results confirm the importance of the hydraulic conductivity in the rates of water extraction by plant roots under constant climatic conditions.

Water uptake per unit length was calculated by dividing the sink term by the root density (length) in that segment of the column (Table 1). The results show that uptake per unit root length was closely related to the sink term. In the upper part of the column where the sink was small, uptake per unit root length was small and increased as the magnitude of the sink increased. This suggested that roots were absorbing water from the region where it was readily available. The results presented in Fig. 6 indicate that the major cause for the decreased uptake per unit root length in the drier parts of the column was more likely related to transmission characteristics of the soil than to root age and

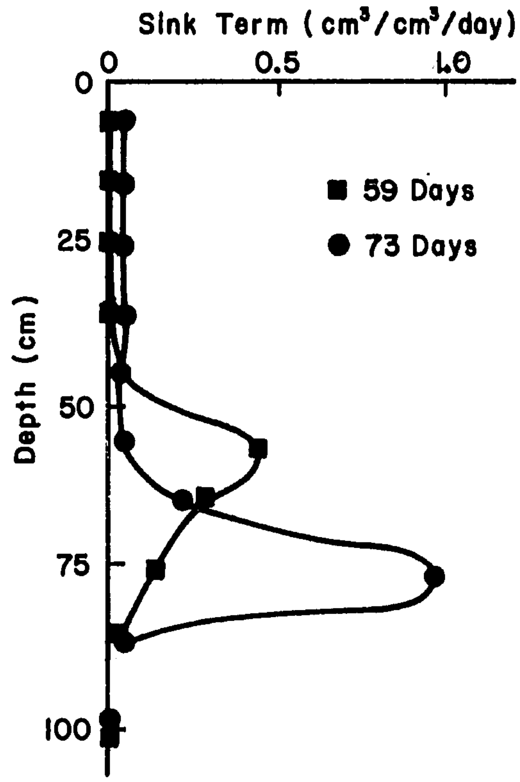


Fig. 7. Examples of the sink term profiles vs. depth at 59 and 73 days after planting (18).

Table 1. Water uptake per unit root length (cm^3/cm root/day) vs. depth.

Depth (cm)	Days after planting 59	73
0-10	.00042	.000028
10-20	.0026	.00054
20-30	.0034	.0021
30-40	*	.0021
40-50	.0057	.0029
50-60	.43	.0097
60-70	.18	.076
70-80	.11	.67
80-90	.023	.035
90-100	-	-

*Values of sink term were positive.

suberization. Since the soil was nearly saturated just above the water table, the decrease in uptake per unit length below the zone of maximum uptake per unit root length was probably due to poor aeration. The results suggested that in the presence of a water table, an aeration factor is needed in modeling the sink term in addition to any other factors that may influence physiological activity of the plant. These data further show that increased plant uptake of water was not necessarily associated with increased water uptake per unit length in the region of maximum sink activity. Maximum values of uptake per unit root length agreed reasonably well with those suggested by Gardner and Ehlig (26).

In the region of maximum uptake, it was difficult to distinguish between the effects of increased water availability, root age, and root resistance on water uptake; however, the high values of uptake per unit length suggested a low root resistance in this region.

In the studies of Reicosky et al. the large increase in root density, both on a dry weight basis and on a length basis in the 50 to 80 cm depth, corresponded to the location of the maximum sink term in the latter part of the experiment. The increase in the maximum sink appeared to be partly related to the increase in root density. However in the remainder of the column there was little relationship between sink profiles and root density profiles.

A comparison of the sink profiles and the root density profiles indicates that in the presence of a water table, a small portion of the root system can be responsible for the major portion of the water uptake. Summing both sink strength and root length for the 50 to 70 cm depth at 59 days and comparing these data with the sink strength and root length in the whole column showed that about 22 percent of the root system absorbed about 83 percent of the water. Similar calculations for the 60 to 80 cm depth at 73 days after planting showed that 23 percent of the root system was absorbing 94 percent of the water. Using root density on a dry weight basis in the same depth increments, 30 and 20 percent of the root weight absorbed the same proportion of water 59 and 73 days after planting respectively.

The uptake of water required to meet evapotranspiration demand can be limited by factors in the soil as well as in the plant. Unsaturated hydraulic conductivity has been shown as one of the major limiting factors in water uptake by plants. The amounts of water absorbed from the upper part of the column were negligible compared with that absorbed from the capillary fringe. The zone of water uptake, as indicated by the sink strength was initially near the surface, but moved progressively downward with time. Thus for soybeans grown in the presence of a water table the study of Reicosky et al. indicated that (i) the magnitude of the sink term increased as the plant's demand for water increased, (ii) the hydraulic conductivity was of fundamental importance in determining the magnitude and distribution of the sink term, (iii) there was a poor relationship between the root distribution and sink profiles and (iv) the increased demand for water by plant tops can be met by an increase in root density in the zone of maximum sink strength or by an increase in uptake per unit root length where water is readily available.

Manor (27) presented a model to predict the zone of water uptake by plant roots under a constant boundary condition in which the water table is maintained at a fixed, shallow depth. Maintenance of shallow water table or the nearly continuous supply of water to the plant with trickle or sprinkler system constitute a constant or nearly constant boundary condition. The hydraulic conductivity of the soil as a function of pressure head and the transpiration rate are the only information that is required for the prediction. Models, such as that of Whisler et al., require the root distribution information as an input and cannot predict the rooting pattern in the soil.

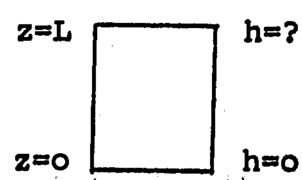
In developing the model of Manor, consideration was given to the fact that when a plant is growing in a soil with a given water table and the flow of water reaches steady state, then the zone of maximum uptake of water by plant roots is relatively narrow, i.e. most of the water uptake is concentrated at a given depth. The upward water flux from a water table and the subsequent removal from the soil surface under steady state condition and in regions where there are no roots is uniquely defined by the solution of the following equation.

$$L = - \int_{o}^{-h(L)} \frac{1}{1 + \frac{\theta}{K(h)}} dh \qquad [11]$$

where L and $h(L)$ are the depth to the water table and the pressure head at the soil surface respectively.

The derivation of equation [11] is approached as below.

Darcy equation for unsaturated upward flow is assumed as



$$\theta = -K(h)\left(\frac{dh}{dz} + 1\right)$$

$$-\frac{\theta}{K(h)} = \frac{dh}{dz} + 1$$

$$-\left[1 + \frac{\theta}{K(h)}\right] = \frac{dh}{dz}$$

$$\int_0^L dz = -\int_0^{h(L)} \frac{dh}{1+\frac{\theta}{K(h)}}$$

$$L = -\int_0^{h(L)} \frac{1}{1+\frac{\theta}{K(h)}} dh$$

For a given water table depth the upward water flux is a function of K(h) and h(L). For hydraulic conductivity functions that seem to be representative of known soils and for a fixed column length the solution of the above equation predicts that a limiting flux, θ_{Lim} is approached as h_L approaches minus infinity. The limiting flux decreases as L increases. Thus for a given upward flux there exists a finite maximum distance above the water table beyond which that flux cannot be maintained.

$$z = -\int_0^{-\infty} \frac{1}{1+\frac{\theta_{Lim}}{K(h)}} dh \qquad [12]$$

where z is the distance above the water table. In most soils due to the strongly nonlinear character of the conductivity function, the upward flux is very close to the limiting flux when the pressure head at the soil surface is not very negative (-50 to -300 cm of water). Based on this consideration and with the assumptions that: (i) the zone of water uptake is narrow enough that it can be represented as a horizontal plane, (ii) a steady state condition on a daily average flux basis is reached, (iii) the transpiration rate of the plant is known and assumed to be equal to the water flux from the water table, and (iv) the conductivity function of the soil is known, the following conclusion was drawn for conditions where the plant is growing in a soil in which the water table is maintained at a fixed shallow depth:

"The transpiration rate is considered to be θ_{Lim}. All the upward flux from the water table is considered to disappear through the plant roots to the atmosphere at a plane which is at elevation z above the water table. This plane is considered to be the plane of water uptake and its elevation z is calculated by equation [12]. The plane of water uptake is assumed to represent the main zone of water uptake by the plant. The zone of water uptake cannot be higher than the predicted plane of water uptake by equation [12], but may be lower. Furthermore, the predicted location of the plane of water uptake is assumed to be independent of the plant in the sense that the nature of the plant is not considered in the calculations."

With this objective in view, experimental studies were undertaken using plants grown in columns of soil having a fixed water table depth. The water table was also varied. The predicted plane of water uptake was compared with experimental results. Plant water potential was measured with a thermocouple psychrometer and a pressure bomb. This information was used to calculate the water uptake by equation [9] as proposed by Whisler et al. Information was obtained on the hydraulic properties of the soil. Pinto beans

(*Phaseolus vulgaris*) plants were used to extract water from the soil. Water withdrawal profiles calculated by the steady state equation [5], measured when the plants were growing in soil with a shallow water table were compared with the locations of the planes of water uptake calculated from equation [12]. Altogether the comparisons include five different soil and six different plants having a range of transpiration rates and water table depths.

Throughout the growing season the water table in the column with dune sand was maintained at a depth of 73 cm from the soil surface and in the other two columns at depths of 100 cm and 128 cm from the soil surface. During the first six weeks after planting the water table in the fourth column was maintained at a depth of 98 cm and then lowered to 125 cm from the soil surface. For each column the upward water flux as a function of elevation was calculated from the hydraulic gradient and hydraulic conductivity. The measured zone of maximum uptake of water by plant roots was compared with that predicted by the model suggested above.

As an illustration Fig. 8 refers to the observations in column 4 (Tripp fine sandy loam), where the water table was maintained at a depth of 98 cm from the soil surface during the first six weeks after planting and then lowered to 125 cm for the rest of the growing period. The source term profile was concentrated between 68 and 88 cm above the water table with peak withdrawal at 80 cm. The upward water flux was 2 cm day^{-1}. The plane of water uptake was predicted to be

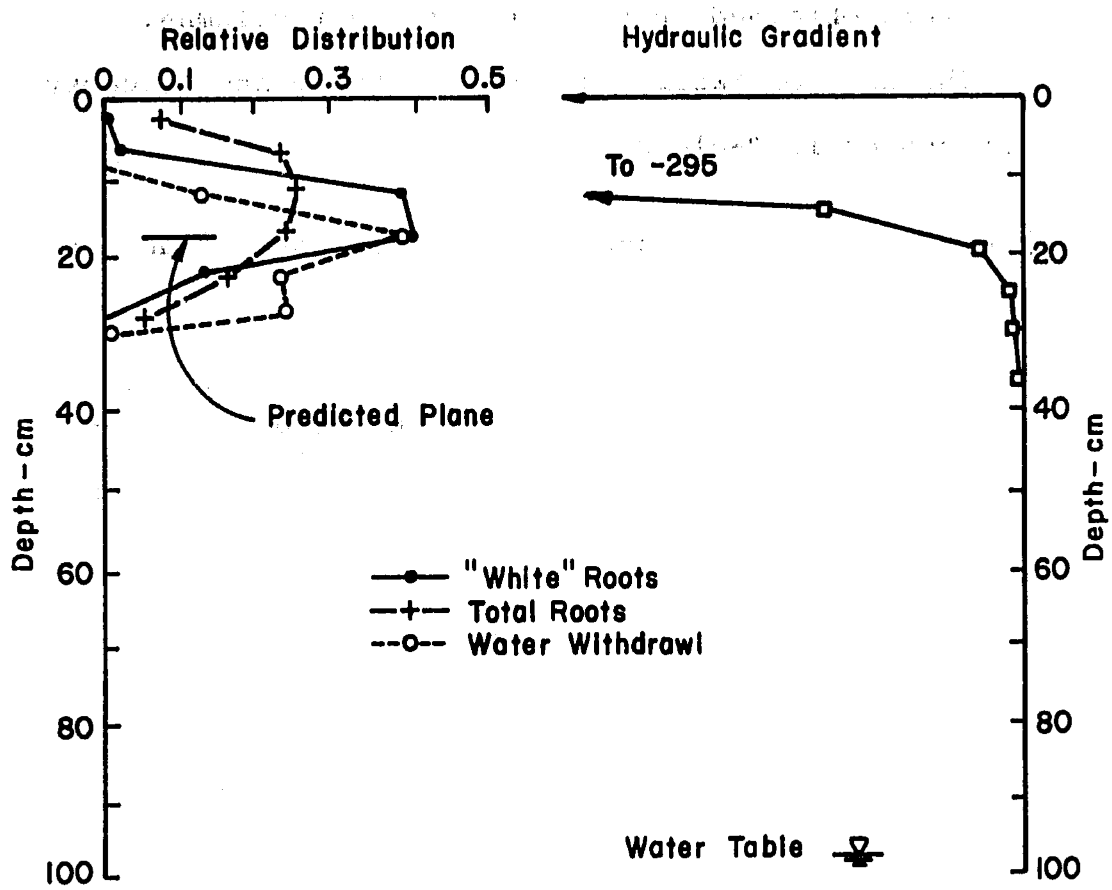


Fig. 8. Depth distribution of (a) water withdrawal, length of roots per unit volume of soil and predicted plane of water uptake, and (b) hydraulic gradient. All distributions are 6 weeks after planting in Column 4 (Tripp fine sandy loam) when the upward water flux was 2.0 cm day^{-1}. The water table was maintained at a depth of 98 cm (27).

80 cm above the water table. This refers to the conditions just before lowering the water table to 125 cm. Similar results were obtained in the case of other columns.

The data of Manor, Gardner and Ehlig and Reicosky et al. is presented in Table 2.

Table 2. Water table depth, predicted zone of uptake and withdrawal.

Column	Soil	Crop	Water table depth (cm)	Predicted zone of uptake (cm)	Source term concentrated in between (cm)	Peak withdrawal (cm)
Data of Manor						
2	Tripp fine	Pinto Beans	128	90	63-90	80
3	Sandy loam	"	100	55	47-67	60
4	"	"	98	80	68-88	80
4	"	"	125	97	85-105	95
Gardner and Ehlig						
	Pachappa	Cotton	110	55	50-75	55
	Fine sandy loam	Sorghum	110	82	60-98	85
	"	Pepper	110	70	30-72	60
Reicosky et al.						
	Dickinson Sandy loam	Soybeans	100	22	15-40	25

The data presented in Table 2 indicate that the location of the predicted plane agreed with the zone of water withdrawal under different conditions of soil type, plant species, water table depth and transpiration rate. The predicted location was in reasonable agreement with the zone of water withdrawal regardless of plant species provided the plant is growing in the soil and transpiring water supplied from the water table. Poor aeration in the nearby saturated soil close to the water table could be a limiting factor in root development and water uptake in this region. Negligible upward flux in the upper part of the soil is the limiting factor in water uptake in this region.

C. Soil Water Evaporation in the Presence of a Water Table

In order to determine what depth the water table should be maintained for the purpose of productive agriculture, the relation between depth to water table, soil properties and evaporation rate must be known. This information is also desirable when estimating water loss from soils by evaporation and estimating the amount of ground water available to plants due to the upward movement of water from a water table.

The effect of depth of water table upon evaporation rate was studied experimentally by Gardner and Fireman (28). The experimental rates of evaporation of water from laboratory soil columns were compared with the theoretical solutions of the steady state unsaturated moisture flow equation and a good agreement was found between the two. The results for Pachappa sandy loam are shown in Fig. 9.

The capillary conductivity of two soils studied (Pachappa fine sandy loam and Chino clay) are shown in Fig. 10. The two soils represented two quite different soil textures.

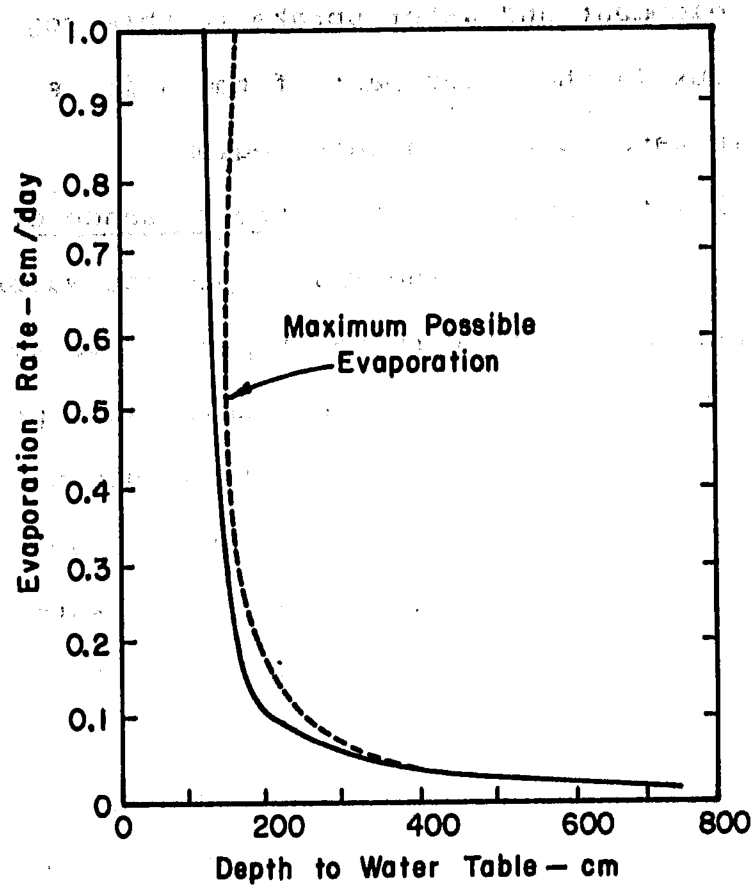


Fig. 9. Theoretical and experimental rates of evaporation of water from a column of Pachappa sandy loam as a function of depth to water table (28).

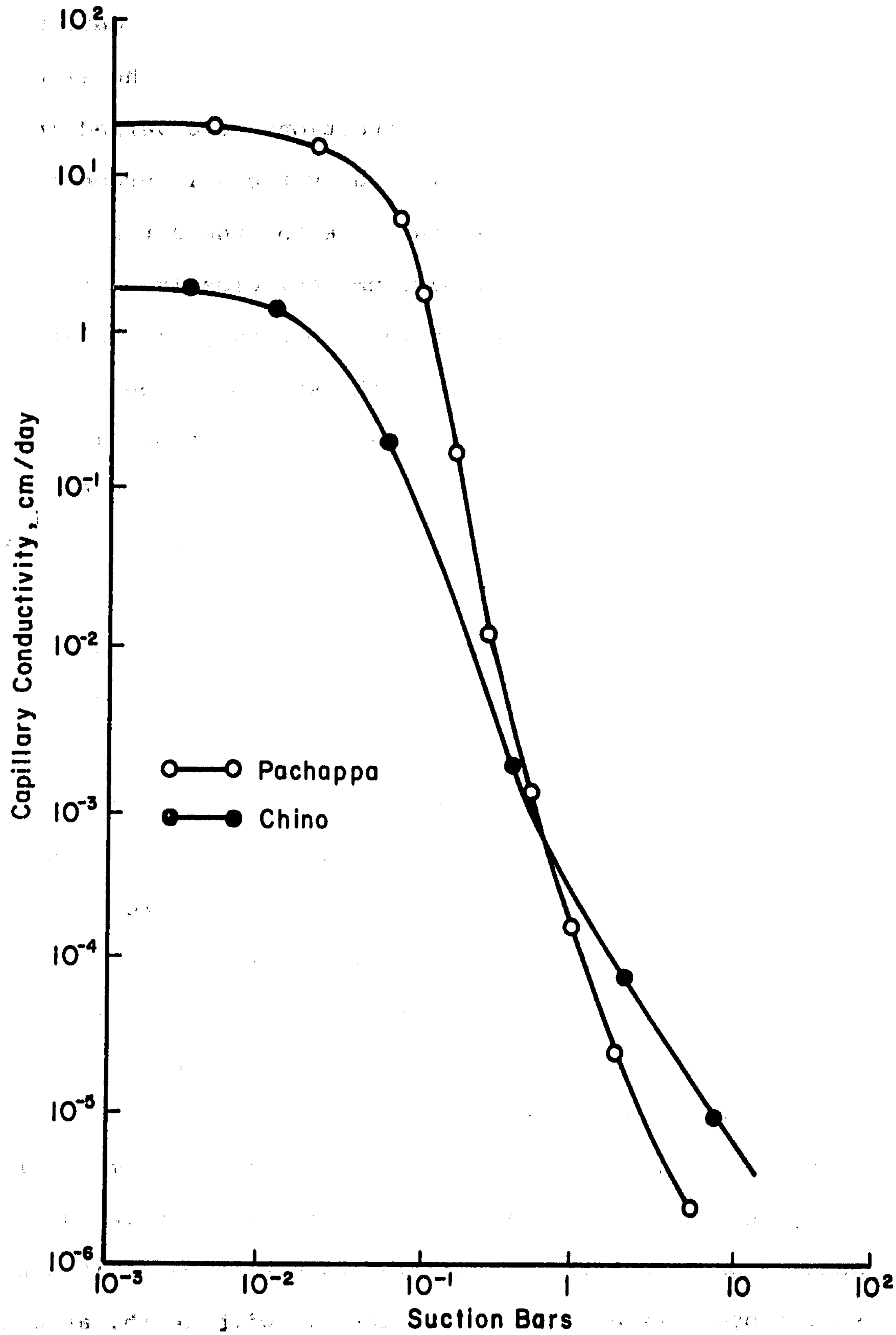


Fig. 10. Capillary conductivity as a function of matric potential (28).

The capillary conductivity and soil suction data were used to calculate the evaporation. Results of the experiment in which external evaporative conditions were varied indicated that evaporation was limited by the soil properties only. At the greater water table depths the actual rate approached the theoretical maximum very closely. Since the potential evaporation rate in the laboratory was relatively low, the experimental values at the shallower depths do not approach the maximum as closely as they might be expected to under the higher evaporation conditions frequently found in the field. The agreement between the experimental values and those calculated from the suction is excellent.

These studies also show that there are two maximum evaporation rates from a soil in which there is a water table. One is the potential evaporation rate determined by the external conditions approximated closely by the rate of evaporation from a free-water surface, and the other is the maximum rate at which water can be transmitted upward through the soil from the water table to the soil surface.

The depth at which a water table should be maintained can thus be determined. Lowering the water table from the surface to a depth of 60 to 90 cm would be of little use in most soils, since evaporation in this range is limited largely by the external conditions. As the water table is lowered below 2 or 3 feet the evaporation rate becomes limited by the soil properties and decreases markedly with depth, as can be seen from Fig. 9. Lowering the water table from 90 to 180 cm in Pachappa fine sandy loam would decrease the evaporation rate by a factor of eight. When the water table is down to 10 or 12 feet, however, further lowering reduces the evaporation rate only slightly. Upward movement and evaporation of water is possible with the water table as deep as 25, 30 or more feet, but the rate will be low.

Similarly the data collected at Lahore, Pakistan, indicated that soil evaporation with water table at 10 feet below surface was about 3 to 5 percent of the free water surface evaporation (3).

Gardner (29) concluded that in most soils water cannot move upward more than about 1 m at a rate sufficient to supply the needs of a transpiring plant.

D. Effect of Water Table Depth on Irrigation Requirements and Crop Yields

The nearness of the water table to the soil surface has a profound influence on the growth of crops. In many cases the irrigation requirements are substantially reduced without reducing crop yields.

Studies (30) were carried out in Pakistan at Chakanwali Experimental Station where 2 foot and 4 foot deep field drains were used to control the water table. Cotton was grown to maturity with only one irrigation and 8 inches of monsoon precipitation. Under deep water table conditions cotton normally requires 7 to 8 irrigations amounting to approximately 30 inches of irrigation water. Thus under high water table conditions the crop met its balance moisture requirements from the groundwater. At three other experimental stations with high but fluctuating water table depth, it was possible to mature a rice crop with 40 inches of irrigation with a water table between 2 to 4 feet as compared to 60 inches needed under deep water table conditions. The data pertained to the years 1963-66 and is presented in Table 3.

Table 3. Average yields of rice (maunds*/acre) at different stations with varying water applications

Irrigation (inches)	CRF Experiment Station** water table 2 - 4 ft.				MRF Expt.*** Station water table 12 ft.		BRF Expt. Station**** water table 22 ft.		
	1963	1964	1965	1966	1963	1964	1964	1965	1966
30	13.75	24.90	20.50	13.50	8.80	16.10	12.10	3.68	4.05
40	17.25	30.40	27.20	18.75	9.25	23.10	12.50	4.76	3.45
50	12.00	27.75	25.48	16.50	10.45	26.70	15.50	5.25	5.30
60	12.50	24.75	22.45	14.50	11.65	33.50	18.66	6.25	8.40

*1 maund = 82 pounds
**CRF - Chakanwali Reclamation Farm
***MRF - Moharanwala Reclamation Farm
****BRF - Ballewala Reclamation Farm

From this data it can be inferred that the irrigation requirements are reduced as the water table is raised. At the CRF Experimental Station where the water table was 2 to 4 feet the best yields were obtained with the 40 inch application as compared to 60 inches required under deep water table conditions (BRF) indicating a reduction of 33 percent in irrigation requirements. Similarly, the irrigation application of 50 inches at the MRF Station gave comparable yields as compared with 60 inches at BRF indicating a reduction of 16 percent. The data bring out the profound influence of water table on irrigation requirements.

The increase or decrease in water table affects the cropping pattern also. With a rising water table in the absence of drainage, low water requirement crops gradually go out of production and, as the area gets submerged under water, even crops like rice which can stand excess moisture cannot be raised.

The rise of water table in the Indus Plains of Pakistan has had a marked effect on cropping patterns after the inception of the various canal systems in the absence of effective drainage. In the perennial area with a year-round water supply of the Punjab, the kharif (summer) acreage under cotton has decreased from 56 percent to 35 percent. Where the water table has risen to within 5 feet of the surface cotton has practically gone out of cultivation and occupies only 3 percent of the kharif acreage. Cotton forms only 28 percent of the kharif acreage in areas with water table in the range of 5 to 10 feet. In areas with water table 10 to 15 feet deep, cotton is grown on 5 percent of the land as compared to an area with water table more than 15 feet. In the Sind, the case of Dadu division is typical. Cotton was 44 percent of the kharif acreage in 1936-38. After the water table raised to near the surface there was a rapid decline in cotton acreage. It now occupies only 2 percent of the kharif acreage. Similarly, other water sensitive crops such as maize, gram, oilseeds, etc., have gone out of production. There has been a corresponding increase in the acreage under rice in the zones with rising water tables. In areas having water tables within 5 feet, 60 percent of the kharif acreage is under rice. Rice acreage decreases to 24 percent for areas in the 5 to 10 foot water table range, 14 percent in the 10 to 15 foot water table zone and only 11 percent in areas with water table deeper than 15 feet.

Van Schaik et al. (31) determined the water uptake pattern and evapotranspiration by nonirrigated orchard grass in the presence of shallow water tables of 91, 122 and 152 cm in nonweighing lysimeters. One-half of the lysimeters were seeded to orchard grass (*Dactylis glomereta*) and the other half were kept bare. At approximately one week intervals the water content of profile in each lysimeter was measured with a neutron moisture meter. Both rainfall and the upward flux from the water table were recorded daily. The total evapotranspiration over a period of three months was 38.8, 37.2 and 34.9 cm for water table depths of 91, 122 and 152 cm, respectively, which accounted for 70, 61 and 51 percent of the total evapotranspiration. The remaining water was supplied by the soil and the rainfall.

Total upward movement of soil water during the four years of studies by Van Schaik, et al. was not great enough to cause salt accumulation near the soil surface. However, during the relatively dry summer of 1967, salinization of the root zone above the capillary fringe probably occurred under grass cover. Without plant cover this salization would not occur. Thus, summer fallow was thought to help avoid salt accumulation and salinization of the surface soil.

In the U.S.S.R (32) the general tendency is not to lower the water table more than is essential for salinity control. When the water table is lowered by deep drainage, the quantities of water required for irrigation are increased considerably. Two to three more irrigations per season are required with a low water table as compared to a more shallow one which contributes to the water requirements of the crops.

Under high water table conditions the nitrogen (N) supply is disturbed, however, and crop yields are affected. In studies carried out in the Netherlands (33) on a long term experiment in the field, it was found that yield reductions were severe for several crops resulting from permanently high water tables. Reduced yields sometimes can be compensated by increasing the normal amount of N fertilizer by a considerable quantity. From this, the losses in nitrogen could be estimated due to decreased nitrification, decreased mineralization of complex nitrogen compounds, and increased losses of reduced nitrogen compounds.

From the data obtained it was concluded that the N production per hectare (ha) in the soil has been as follows for different water levels:

150 kg N at ground water level 1.50 m below soil surface

120 " " " " " " 0.90 m " " "

55 " " " " " " 0.40 m " " "

The total N decrease, due to hydrological conditions, appears to be 30 kg/ha when the ground water level increases from 1.50 m to 0.90 m below soil surface and 95 kg/ha with an increase of the water table from 1.50 m to 0.40 m below soil surface.

These "losses" caused yield reductions which could not completely be compensated by increasing the N supply. Probably other nutrients may have become deficient under conditions of high ground water levels.

The average relative yields where no supplementary N was applied on some crops grown at different water levels are shown in Table 4.

Table 4. Average relative yields of crops with no applied N at different water tables.

Crop	Depth of water table (in m)	Relative yield (in %)	
		Grain root	Straw
Cereals	1.50	100	100
"	0.90	88	87
"	0.60	77	78
"	0.40	55	59
Broad beans	1.50	100	100
"	0.90	90	100
"	0.60	84	95
"	0.40	79	86
Sugar beets	1.50	100	
"	0.90	92	
"	0.60	84	
"	0.40	71	

In irrigated areas, high groundwater tables, nonsaline in character, contribute considerably to plant water supply by capillarity. This means that surface irrigation can be reduced. However this advantage must be compared to the disadvantage of some yield reductions where the water table is too high. The benefits of a decrease in surface irrigation has to be compared with the cost of additional N application to justify the selection of management method.

Barakat et al. (34) studied the effect of water table depths of 40, 70, 100, 130 and 160 cm from the soil surface on the growth of cotton. Groundwater salinities were 2200 and 4200 ppm for the seasons 1964, 1965 and 1966 and 8200 ppm for 1967.

With a groundwater salinity of 4200 ppm or less the yield of cotton approached the maximum at a water table depth of 160 cm. By raising the water table higher than 160 cm the yield declined rapidly and the soil texture became an important factor. In these studies a sandy clay loam produced less yield than a clay loam soil and a calcareous sandy clay loam took an intermediate position. Salinity effects were absent. Response to N fertilization was affected by the depth of the water table. At high rates of N fertilization different textured soils were equal in production, but were different at lower application rates.

The effect of water table height on soil aeration and crop response was studied by Hiller et al. (35). Grain sorghum was grown in field lysimeters in which the water table was regulated automatically. Undisturbed soil cores which were one meter in diameter, 2 m deep, made up the lysimeters. Rainfall was kept off the lysimeters with a shelter system. Drastic reduction both in quantity and quality of grain sorghum yield occurred when water tables were maintained at 30 and 60 cm as compared to the 90 and 120 cm depth. In general reduced growth of grain sorghum occurred with the shallower water tables. Considerable crop oxygen stress occurred in the 30 cm depth treatment in which oxygen diffusion rates never exceeded 0.2 millionths of a g per sq cm per min. in the root zone during the growing season. Detrimental oxygen stress also occurred in the 60 cm depth treatment where oxygen diffusion rates in the crop root zone ranged from 0.4 to 0.9 millionths of a g per sq cm per min. during the growing season. Leaf temperature and leaf diffusion resistance were not appreciably affected by oxygen deficiencies in the crop root zone.

The effect of depth to water table and plant density on evapotranspiration (ET) rate in southern Florida was studied by Stewart and Mills (36). Significant differences in ET of sod crops grown on sandy soils with 12, 24, and 36 inch water tables occurred only during periods of very low rainfall. Based on these data, ET for sod crops with a 36 in. water table may be expected to be about 88 and 78 percent of ET for a 24 in. and 12 in. water, respectively, during extended rain-free period.

The influence of water table on water and some nutrient losses was studied by Barakat et al. (36). Average water loss by deep percolation was found to decrease steadily with increasing depth of water table in a lysimeter experimentation on cotton and maize crop where five depths of water tables were varied from 40 to 160 cm. Water losses were 35 cm and 22 cm for water table depths of 40 cm and 70 cm. Water loss was 6 cm at a water table depth of 160 cm. Average irrigation water for the whole growing season was 65 cm. Nutrient losses by deep percolation followed that of water; they were found to be 27 kg N, 88 kg K and 135 kg K per hectare for the 40 cm water table, and 17 kg N, 55 kg K and 0.083 kg P per hectare for the 70 cm water table. Losses of K and P were greater in higher soils.

A four year lysimeter study by Namken, et al. (38) determined the contribution of shallow saline water on cotton yields on permeable soils. Controlled water tables at 91, 183 and 274 cm contributed 54.4, 26.4 and 17.3 percent of total water used for a high moisture treatment, and 60.6, 48.9 and 39.2 percent under low moisture treatment. Soil profile depletion, rainfall, irrigations and water table additions comprised the total water. Water uptake from the 274 cm table was strongly related to capillary zone salinity. Lint yields were related to total water and capillary zone salinity. Moderate capillary zone salinity (EC of 10 to 14 mmhos/cm) reduced monthly and seasonal water use compared with low salinity (EC of 2 to 3 mmhos/cm). High moisture treatment delayed seasonal water use.

The effect of varying depth of water table (0.30, 0.60, 1.2 and 1.9 m) on crop yield was studied in lysimeters by Collier et al. (39). Yields were higher in the presence than in the absence of a water table, the relative increase depending on the root system of the various species. A high water table did not affect yields adversely. For perennial fodder crops the optimum water table was high in the first year and lower in the subsequent years or with succeeding costs during the current year.

It was established that a high water table of 50-60 cm in the spring and 80-90 cm in summer promoted the development of apple trees on sandy soils (40). High groundwater resulted in an average of 298 roots > 0.1 cm diameter and a root distribution mainly in the 10-30 cm layer of the soil (unfavorably affecting the stability of trees) as compared with only 155 roots and a root distribution down to 50 cm under conditions of low water table of 150 cm in spring and 220 cm in summer. A water table of 100-120 cm was recommended for planting apple trees on EMIV root stock in sandy soils.

The effect of ground water on production of some horticultural crops on clay and loamy soils was studied by Valk, et al. (41). Gladiolus, cauliflower, early red beet, savoy cabbage and onions were grown on heavy clay top soil, with sticky clay or light fine sandy clay subsoils, and light fine sandy clay profiles. Groundwater tables varied from 20 to 160 cm. On heavy clay top soils cultivation was late and yields were unaffected by groundwater levels of 30-160 cm. Yields on heavy clay top soils were not affected by the different subsoils. Groundwater levels above 50-60 cm depressed yields, with the exception of gladiolus. The yield of gladiolus was not unfavorably affected even with a level of 30 cm. Early cultivation was possible on light fine sandy clay where crop establishment was not affected by weather. On these soils production of all crops reacted to groundwater levels.

Purvis (42) studied crop production on high water table soils of New Jersey. During an 8 year period on these sandy podsoils, mean depth to water table in the growing season in years of normal rainfall was about 16 inches at one site and 44 inches at another. The surface soil consisted of 86 percent sand, 10.5 percent silt and 3.5 percent clay and retained only 12.3 percent moisture at field capacity. The moisture content at wilting point was 3.0 percent, a level not reached during the study. The narrow moisture gradient between surface soil and water table during periods of drought suggests that moisture movements in the upper profile occurs mainly as water vapors during such periods. Apparently soils having depths of 2 to 4 feet to water tables in normal seasons would provide near ideal moisture conditions for crop growth during both dry and wet seasons. With occasional supplemental irrigation in dry seasons soils of

2 feet higher elevation would probably supply sufficient moisture to crops.

E. Availability of Water to Plants

Water is essential to the life and growth of plants. It is the main constituent of the protoplasm and makes up 85 to 95 percent of the fresh weight of most of their green tissues. Plant-water relations include three processes: water absorption, ascent of sap and water loss by transpiration.

To determine the amount of soil moisture available to the crop, it is necessary to know from what depth of soil the plants get their moisture, or their moisture-extration pattern and how fast they use moisture.

Gardner's solution (19) of the flow equation already referred to reveals that the suction gradient between root and soil necessary to maintain a given rate of water uptake by the root, i.e. a given transpiration rate, is proportional to the rate of water uptake or the potential transpiration rate and inversely proportional to the capillary conductivity of the soil.

The capillary conductivity of soil decreases rapidly with increasing soil suction. Consequently, as the soil dries, large suction gradients develop between the root and the soil around it. In the case of passive absorption, water movement through the plant arises from a gradient in water potential between the transpiring leaves and the roots. This gradient is assumed to be proportional to the transpiration rate. Thus, to maintain transpiration in a drying soil when the capillary conductivity is decreasing and the suction at the plant root is increasing correspondingly the water potential in the leaves must continually increase so that necessary water potential gradient between leaf and root is maintained. The rise in water potential in the leaves is accompanied by a decrease in turgor pressure resulting in closing of the stomata and dehydration of the leaves.

Likewise, an increase in the potential transpiration rate will hasten the increase in the water potential of the leaves leading to a more rapid fall in the turgor of the plant with decreasing moisture supply.

Thus we expect transpiration rates to decline with decreasing soil moisture content and we expect that this decline will be evident at higher and higher soil moisture contents as the potential transpiration rate increases. The particular soil moisture content at which the decline in transpiration occurs will also depend on the soil properties. In soils where most of the water is held at low suction, the decline should not be evident until most of the "available" soil water has been extracted. In soils wherein suction increases rapidly as soil moisture content decreases, the decline in transpiration should be noticeable at comparatively higher moisture contents. Since the decrease in permeability of the plant and the consequent decrease in transpiration result from the turgor-induced changes such as closing of the stomata and dehydration of the leaves, one expects that soil moisture content at which transpiration rate decreases should be coincident with the soil moisture content at which the plant wilts. That is, the wilting point will also be expected to vary with soil moisture properties and with the potential transpiration rate.

In brief, the availability of water to the crop depends on a combination of soil, crop and climatic factors. The water status of the plant tissues depends on (43):

(a) resistance to flow of water in the soil which varies with water content;

(b) resistance to flow from the stomata into the atmosphere, which varies with atmospheric conditions; and

(c) resistance to flow within the roots and other tissues of the plant, which depends on physiological factors and is by no means constant. Hence, it is usually impossible to predict the internal water status of a plant from conditions in the soil alone or the atmosphere alone, and it is possible for a plant to wilt with abundant water in the soil and to remain turgid when the soil is relatively dry.

The principal plant factors which affect the availability of the water are rooting characteristics and the ability to withstand an adverse water balance. Young plants with an underdeveloped rooting system may be adversely affected at a level of soil moisture at which full-grown perennial plants, such as most grasses, remain unaffected. The latter have a wide and deep root system which thoroughly permeates the soil to a considerable depth. Wheat plants with a well-developed root system were found to be capable of absorbing water at tensions greater than 26 atm. (44). The moisture absorbed at levels below wilting point was not effective in maintaining vegetative growth, but affected the yield and quality of the grain (45).

Summing up, it may be said that the growth and development of plants are influenced by their internal water balance, which in turn depends on both water intake and water expenditure by the plant. Therefore, water availability to the plant will depend not only on soil moisture conditions but also on atmospheric conditions and plant characteristics.

Movement Through the Plant and Transpiration

Water movement through the plant is facilitated by the presence of specialized elongated cells (tracheids) or row cells with the ends broken down forming a more or less continuous system of "vessels." Tracheids and/or vessels constitute the main functional components of the xylem through which water can flow with a minimum of resistance from the roots, through the stem, and into the leaves. This is the situation in all normal vascular and other "higher" plants including the seed plants or spermaphyte to which virtually all crop plants belong (46). There are three interrelated processes in plant-water relations, viz. water absorption, conduction and transpiration. Reference to the first two has already been made. Investigations carried out on transpiration reveal that the water lost from a plant by transpiration is far in excess of the water used in the plant for normal growth purposes. With the gradual scarcity of irrigation water an understanding of the transpiration process has become important.

Two viewpoints have been advanced in this connection. According to one viewpoint transpiration is a necessary evil and according to the other an unavoidable evil. Transpiration is, to some extent, an evil because inevitably absorption of water lags behind transpiration causing water deficits in the plant tissues. Water deficits cause adverse effects on photosynthesis and on growth, with disruption of metabolic processes, and in extreme cases result in death of the plants.

Transpiration is considered a necessary evil because the foliage of a crop intercepts a quantity of radiation that is far in excess of its ability to effectively utilize. Leaves subjected to a heavy radiation load must be able to dissipate the excess energy quickly or else their temperature would rise to lethal levels within less than one minute (47).

Transpiration is considered an unavoidable evil because the absorption of carbon dioxide by the leaf stomata for photosynthesis is essential. A plant structure that makes this possible will inevitably make possible water loss through transpiration. It has been shown that plants which have very low rates of transpiration also have low rates of photosynthesis and grow slowly (48).

Evapotranspiration

Water is lost by evaporation from a bare, moist soil surface at about the same rate as from a free water surface having the same exposure and temperature.

In arid regions, losses of water by evaporation from a crop-canopied soil are relatively low, the main component of water loss being plant transpiration. The surface soil dries quickly preventing water loss from lower layers.

In field measurements it is difficult to distinguish between the two sources of losses. Therefore they are usually estimated together and called evapotranspiration (ET) or consumptive use. When the water supply is unlimited evapotranspiration is equal to the evaporation from a free water surface and, therefore, reaches the highest level possible under the prevailing conditions of radiation, wind velocity, temperature, air humidity, etc. It is then called potential evapotranspiration (PET).

Research on water requirements of crops has shown that, in a large number of cases, maximum yields can be achieved with rates of actual ET that are far lower than PET. In other words, maximum yields are possible even when the level of soil moisture is not constantly maintained at field capacity or even somewhat below (46).

F. Water and Salt Balance

One of the main problems in irrigation is the determination of the quantity of irrigation water to be applied for irrigation and regulation of salinity to meet the optimal situation for crop growth. As such, it is in fact a water balance problem which is linked directly or indirectly with all results of detailed investigations on evaporation, transpiration, soil moisture, groundwater, salinity, etc.

The water balance for the root zone is as below (49)

$I + R + C = E + P + \Delta M$ (all in mm water depth)

where I - Irrigation

R - Precipitation

C - Capillary water supplied to the root zone from the groundwater

E - Evapotranspiration

P - Percolation water

ΔM - Change in moisture content

The contribution of capillary water to the consumptive needs of plants can be worked out, other factors being known.

So far as the salts are concerned, it is usually essential that excess water be applied and allowed to percolate through the soil in order to remove salts by leaching them below the root zone.

An estimation of the leaching requirement may be made from a salt-balance model (50). This model applies to a soil profile that has been irrigated over a long enough period to achieve a steady state condition with regard to salt accumulation and distribution. The rainfall during the growing season is assumed to be insufficient to produce the needed leaching of accumulating salts. The salt-balance equation is:

$$V_{iw}C_{iw} + V_{gw}C_{gw} + S_m + S_f - V_{dw}C_{dw} - S_p - S_c = \Delta S_{sw}$$

where V_{iw}, V_{gw}, V_{dw}, and C_{iw}, C_{gw}, C_{dw} are volume and total salt concentration of irrigation, ground, and drainage water, respectively. V_{gw} refers to that water which moves up into the root zone from the water table. S_m is the amount of salt brought into solution from weathering soil minerals or dissolving salt deposits, S_f is the quantity of soluble salt added in agricultural chemicals (fertilizers and amendments) and animal manures, S_p is the quantity of applied soluble salt that precipitates in the soil, and S_c is the quantity of salt removed from the soil water in the harvested portion of the crop. The net difference between these inputs and outputs gives the resultant change in soil-water salinity (ΔS_{sw}). Under steady water conditions ($\Delta S_{sw} = 0$) assuming no appreciable contribution of salts from the dissolution of soil minerals or fossil salts, or loss of soluble salts by precipitation processes and crop removal (or assuming that the net effect of these opposing reactions is approximately compensated) and uniform areal application of water in the field, and where the water table depth is sufficient to prevent the introduction of salts into the root zone from capillary rise processes, the salt balance equation stated in the foregoing reduces to

$$\frac{D_{dw}}{D_{iw}} = \frac{EC_{iw}}{EC_{dw}}$$

wherein the equivalent depth of water D is substituted for volume and concentration is replaced by electrical conductivity (EC) since EC of a water is a reliable index of its total solute concentration within practical limits (51). Thus, by varying the fraction of applied water that is percolated through the root zone, it is possible to control the concentration of salts in the drainage water within certain limits and, hence, to control either the average or the maximum salinity of the soil water in the profile at some desired level.

The quantity of water needed to reclaim salt-affected soils differs from that required for maintaining a salt balance. For highly saline soils, 30 cm of good quality water for each 30 cm depth of soil will usually provide enough ponded leaching to allow crops to be grown satisfactorily. This generalization is illustrated by the studies of Reeve et al. (52). In these studies the soil was a highly saline (EC>40 mmhos/cm in the surface 30 cm) silty clay loam. The experimental data are approximated by the equation:

$$\frac{D_{iw}}{D_s} = \frac{1}{5\frac{C}{C_o}} + 0.15$$

where D_{iw} is the depth of water leached through a depth of soil D_s and C_o and C are the average salt concentrations in the total soil depth considered, before and after leaching, respectively. In terms of electrical conductivity the equation can be written as

$$\frac{D_{iw}}{D_s} = \frac{1}{5\frac{EC_f}{EC_o}} + 0.15$$

where EC_f and EC_o are the final and initial average electical conductivities of the saturation extract in the soil profile, respectively.

Bernstein et al. (53) established several "rules of thumb" while recommending control of salinity in the Imperial Valley of California. They are (i) 6 in. of water passing through one foot of soil depth will reduce the average salt concentration by 50 percent, and (ii) 1 A ft. of water passing through a 1 ft. depth will reduce the average salt concentration by 80 percent.

Under similar situations where salt affected soils are to be reclaimed, Volobuev and Kovda (54) have proposed two equations for leaching of the salts:

Volobuev's equation

$$N = K \log \left(\frac{S_i}{S_p}\right)^a$$

where N = M^3 of water/M^2 of surface area

K = constant (1 when area = $1M^2$)

S_i = original salinity (g/l)

S_p = permissible salinity (g/l)

a = parameter that depends on soil texture and salinity of the leaching water

Kovda's equation

$$y = (n_1)(n_2)(n_3)400\ x \pm 100$$

where y = depth of leaching water - mm

x = mean salt content in the 2m profile - percent

n_1 = texture coefficient

sand = 0.5, loam = 1.0, clays = 2.0

n_2 = water table depth coefficient

1.5 - 2m = 3, 2 - 5m = 1.5, 7 - 10m = 1.0

n_3 = groundwater salinity coefficient

weak or medium = 1.0

strong = 2.0

very strong = 3.0

e.g. loamy soil with a salinity of 2 percent, groundwater of medium salinity at 8.00m

$y = 1.1.1.\ 400\ .2 \pm 100$

$= 800 \pm 100$mm.

Soil physical properties may limit the desired leaching drainage and cropping designs. Low infiltration rates on fine-textured soils, for example, may make it nearly impossible to get enough water through the profile to achieve leaching.

IV. SUMMARY AND CONCLUSIONS

Water is a scarce resource and a limiting factor to crop production throughout much of the world's arid and semi-arid agricultural regions. In such regions the continuation of a thriving agriculture depends upon the costly development and distribution of water supplies for irrigation.

The importance of water in plant growth has prompted the study of the mechanism of soil water uptake by plants and in recent times a number of reviews have appeared on the theory of transport of soil water. A large fraction of the water that falls on the surface of the soil as rain or irrigation moves into and through the soil during the processes of infiltration, drainage, evaporation, redistribution within the soil and water uptake by plant roots. A major part of all of these phenomena involves flow of water in unsaturated soil.

Crops can benefit from high water tables. There are situations where excess water does not necessarily lead to excess salinity. This is true where groundwater tables are controlled but continued leaching prevents salt accumulation in the root zone. Examples of such circumstances are to be found in many oases in North Africa where drainage is sufficient to evacuate leaching water, but the groundwater table remains high. Regular flooding with fresh river water may have more or less the same effect. Finally when fresh groundwater is flowing continuously through a good permeable subsoil no severe danger for salinization occurs even when the water table is high (54). Upward capillary movement of water will be intensive, but due to low salinity of the groundwater, accumulated salts in the top layers of the soil can easily be leached during irrigation or by rains.

In such conditions, high groundwater tables are favorable and substantially reduce the irrigation requirements.

The next question is the determination of the availability of soil moisture to crop from water tables. In this connection it is necessary to know from what depth of soil the plant roots obtain their moisture or their moisture-extration pattern, and how fast they use moisture.

Gardner's solution of flow equation reveals that the suction gradient between root and soil necessary to maintain a given rate of water uptake by the root, i.e. a given transpiration rate is proportional to the rate of water uptake or the potential transpiration rate and inversely proportional to the capillary conductivity of the soil.

The capillary conductivities of soil decreases rapidly with increasing soil suction. Consequently, as the soil dries, large suction gradients develop between the root and the soil around it. In the case of passive absorption, water movement through the plant arises from a gradient in water potential between the transpiring leaves and the roots. Thus, we expect transpiration rates to decline with decreasing soil moisture content and we expect that the decline will be evident at higher and higher moisture contents as the potential transpiration rate increases. The particular soil moisture content at which the decline in transpiration occurs will also depend on the soil properties.

Manor's model predicted the zone of water uptake by plant roots in which the water table is maintained at a fixed, shallow depth. The hydraulic conductivity of the soil as a function of pressure head and the transpiration rate are the only information that was required for the prediction. The location of the predicted zone of water uptake was verified with an experimental study using bean plants grown in columns of soil in a growth chamber. Similar comparisons were made with results from the literature for cotton, pepper, sorghum and soybeans. This data is summarized in Table 5.

The location of the predicted plane of water uptake agreed with the zone of water withdrawal regardless of the plant species and under various conditions of soil type, water table depth and transpiration rate. The approach was found to be applicable to a constant boundary condition in which the water table was maintained at a fixed shallow depth.

In the evaporation studies listed in the foregoing it has been brought out that there are two maximum evaporation rates from a soil in which there is a water table. One is the potential evaporation rate determined by the external conditions, approximated closely by the rate of evaporation from a free-water surface, and the other is the maximum rate

Table 5. Water table depth, predicted zone of uptake and withdrawal.

Column	Soil	Crop	Water table depth (cm)	Predicted zone of uptake (cm)	Source term concentrated in between (cm)	Peak withdrawal (cm)
Data of Manor						
2	Tripp fine	Pinto beans	128	90	63-90	80
3	Sandy loam	"	100	55	47-67	60
4	"	"	98	80	68-88	80
4	"	"	125	97	85-105	95
Data of Gardner and Ehlig						
	Pachappa	Cotton	110	55	50-75	55
	Fine sandy loam	Sorghum	110	82	60-98	85
	"	Pepper	110	70	30-72	60
Data of Peicosky et al						
	Dickinson sandy loam	Soybeans	100	22	15-40	25

at which water can be transmitted upward through the soil from the water table to the soil surface. Lowering the water table to a depth of 2 to 3 feet would be of little use in most soils, since evaporation in this range is limited largely by the external conditions. As the water table is lowered below 2 or 3 feet the evaporation rate becomes limited by the soil properties and decreases markedly with depth. Lowering the water table from 3 to 6 feet would decrease the evaporation rate by a factor of 8 and when the water table is down to 10 or 12 ft. further lowering reduces the evaporation rate only slightly.

Nicolaev[55] has suggested the lowering of the water table to about 2 m (6.5 ft.) and has estimated that the irrigation requirements needed would be 50-70 percent.

Kovda, Berg and Hagan[56] on the basis of their experience gained from the study of crop responses to various patterns of groundwater to which the water table may rise and considering various economic and other factors on the relation of depth to water table, quality of groundwater and the danger of salinization as a result of capillary rise have suggested a maximum water table height of 1.5 m (5 ft.) below land surface for a broad range of irrigated conditions. They have further remarked that the depth may not, however, be adequate under excessively high evaporative conditions, highly mineralized groundwater and soils with rapid capillary conduction characteristics.

In the light of what has been stated it appears reasonable to stabilize the water table in the brackish water zone at 5 to 6 feet. With the collection of necessary data on soil water evaporation, hydraulic conductivities and the transpiration rates it would be possible to build a model and predict the zone of water uptake accurately.

The nearness of the water table will have a profound influence on the irrigation needs of the plants. The data gathered in this connection indicate that it may be 30 to 40 percent depending upon soil conditions and plant growth.

In some cases it might be possible to apply only one initial irrigation for germination and no further surface irrigation may be needed.

Leaching formulas have been included to pinpoint that in such a system it would first be necessary to desalinize the soil profile for achieving maximum benefits from the soil as well as the subsoil water.

V. APPLICATION TO PAKISTAN AND RESEARCH NEEDS

Pakistan lies in arid to semiarid zone and has the world's finest contiguous system of irrigation consisting of more than 33 million acres of culturable commanded land under its command. The history of irrigated agriculture in Pakistan reveals that at the time of introduction of canals about 100 years ago the water table was very deep and the alluvium contained salts which were distributed throughout the entire profile. The earthen canals, which were heavily leaking, contributed much to the rise of the water level and seepage was the major component of groundwater recharge. As a result of an extensive inventory of soil and water resources, a long range program for reclaiming the irrigated lands was prepared. The essential feature of this program is a network of tubewells located with an average density of about one per square mile. Groundwater withdrawals will serve the dual purpose of helping to supply irrigation requirements and of providing subsurface drainage. This program is proceeding satisfactorily and is doing well where the quality of subsoil water is within the permissible limits of irrigational use. However, there are areas in Pakistan where the groundwater quality is poor and is a hazard to successful farming. According to an evaluation made by the World Bank Consultants, out of an area of about 30 million acres of culturable commanded land in Pakistan, nearly 48 percent is underlain with good quality water.

Another 16 percent can be used after proper mixing, leaving a balance of 36 percent where the water is saline and not suitable for irrigation. This saline area is not included in the tubewell pumping program. Fortunately in most part of this 36 percent area, there is a fresh water aquifer overlying saline water. Suggestions have been made to recover the fresh water by installation of low capacity skimming tubewells or compound tubewells possessing single or multiple strainers. So far, however, such tubewells have not been installed. Another suggestion has been made to install open or closed subsurface drainage systems and stabilize the water table at a specific depth to take advantage of its proximity to the surface for reducing the irrigation requirements. Under such situations the plants will either require no surface irrigations or will meet a part of their requirements from surface irrigation supplies and a part from the groundwater reservoir. The effluent could be disposed of suitably. With the passage of time it could be possible to leach out salts completely and to build a fresh water zone. Therefore these studies have been initiated to provide an answer to the second suggestion.

There is a need to initiate research in Pakistan on different aspects of water use referred to in the foregoing viz. the location of water uptake, pattern of water use and contribution of the groundwater available to plants under various soil and meteorological conditions of the country. Fortunately a set of large lysimeters is existing at the

Directorate of Land Reclamation of Irrigation and Power Department at Lahore. In these lysimeters it is possible to alter the water table from 0 to 20 feet. The lysimeters are also equipped with soil moisture measuring devices. Therefore, these studies can be undertaken in this set up for providing solutions to many of the water management problems presently faced by irrigated agriculture of Pakistan.

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