SALTMOD: A TOOL FOR THE INTERWEAVING OF IRRIGATION AND DRAINAGE FOR SALINITY CONTROL

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Hitherto, SALTMOD[1] was used to analyse data from pilot areas (Egypt, India, Portugal) where data were available for calibration. For this ILRI symposium it is used to demonstrate the complex inter-actions between irrigation, watertable, salinity and agriculture.

A scenario is presented for an area with a watertable at 10 m depth when irrigation starts. There are two seasons, an irrigation season and a non-irrigation season, when agriculture is rainfed. Initially, during the irrigation season, 100% of the area is irrigated. There is no natural or artificial drainage and no use of groundwater for irrigation.For this scenario, SALTMOD is run in 'automatic gear': the program runs for 15 years without changes in external boundary conditions (e.g. rainfall) but it generates automatic internal responses to changing internal conditions, such as the farmers' responses, which are simulated through in-built mechanisms. For example:

- reduction of irrigated area when irrigation water is scarce,
- reduction in irrigation supply per ha when the watertable becomes shallow,
- abandoning land upon salinization.

In this scenario, the option to change conditions annually and manually ('manual gear') by interactive intervention is not used.

Figure 1 shows that the irrigated area decreases in the first 4 years from 100% to about 80% and in the years 8 to 12 it again decreases to less then 70%. These reductions have different causes.

Figure 1 also shows the reason for the first reduction. It presents the irrigation sufficiency, defined here as the ratio between actual evapotranspiration (ETa) and the potential evapotranspiration (ETp) of the irrigated crops. In the first 4 years, the sufficiency increases from less than 70% to over 80%. Apparently there is not enough irrigation water available to irrigate all crops to full sufficiency and the farmers leave some of the land fallow so that more water can be applied to the remaining irrigated land. The fallow land is not permanent but in crop rotation. Figure 1 shows that the sufficiency increases sharply during the years 4 to 6. To understand the reason of this increase, we look at the behaviour of the watertable.

Figure 2 shows that the depth of the watertable decreases steadily during the first four years, i.e. the watertable is rising. Especially during the fourth year there is a sharp rise, due to a smaller porosity of the soil. From the fifth year onwards, the depth of the watertable becomes less than 1 m, and deep percolation losses can no longer occur. As a result, the irrigation sufficiency increases to almost 100%.

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[1] SALTMOD is an agro-hydro-salinity model developed by Ir. Oosterbaan.

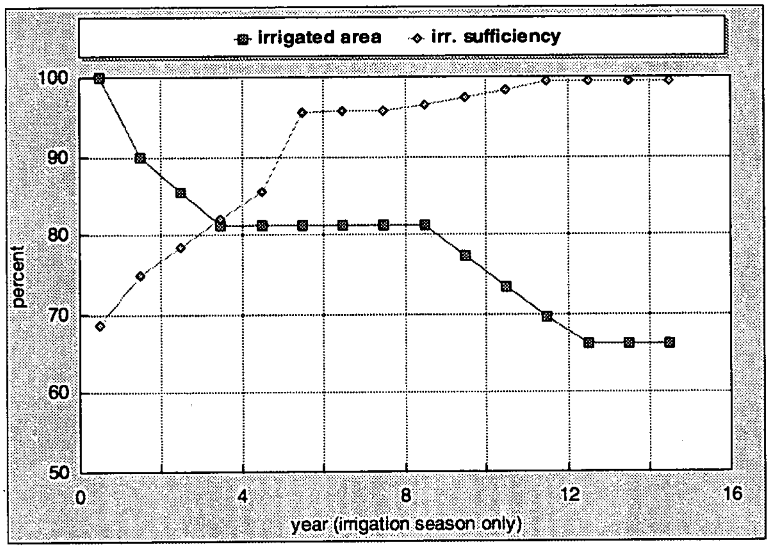

Figure 1. ***Effects of size of irrigated area on irrigation sufficiency***

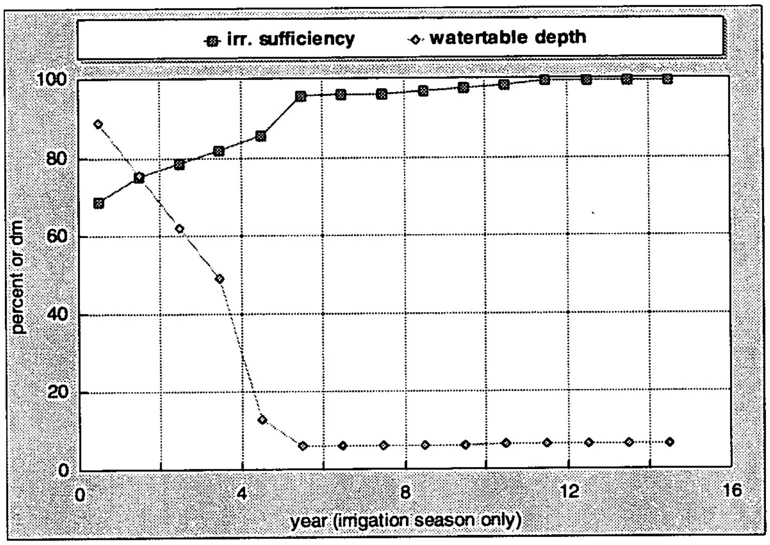

Figure 2. ***Effects of watertable depth on irrigation sufficiency***

The irrigation effectiveness is not only determined by sufficiency but also by efficiency. This is defined here as the ratio between the amount of irrigation water used by the crop (ETi) and the amount of irrigation water applied (Irr). Figure 3 shows that the irrigation efficiency decreases slightly during the first 4 years as the irrigated area decreases and more water can be applied to the irrigated land, so that also the irrigation losses increase. In the years 4 to 6 the efficiency increases sharply from less than 70 to about 80%, although the irrigation application remains stable. After year 8, the irrigation application increases again while the efficiency goes down. An explanation of both features is partly offered in Figure 5 and more fully in the later figures.

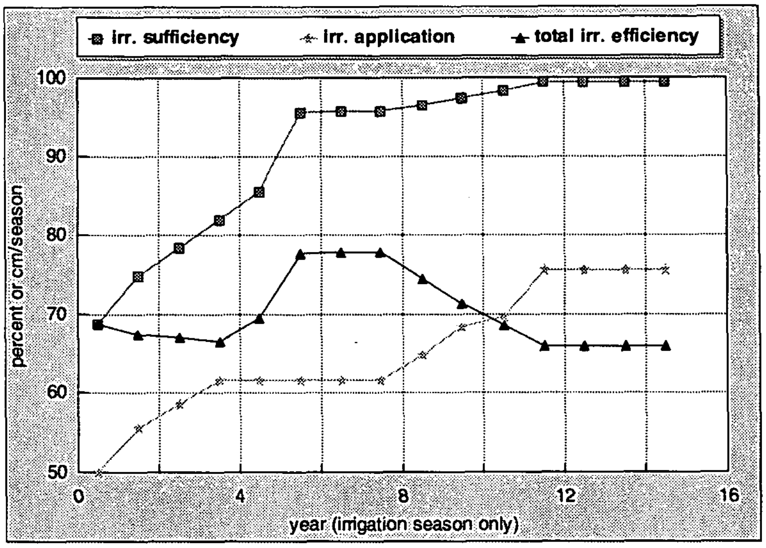

Figure 3. Changes in irrigation sufficiency, irrigation application and total irrigation efficiency

Figure 4 shows that the soil salinity hardly increases during the first four years, as it is checked by the reduction of the irrigated area, higher irrigation applications and more leaching of salts. Hence, the initially low irrigation sufficiency was not the only reason for fallowing the land. Salinity control is a second reason. When, towards year 6, the watertable comes close to the soil surface, deep percolation losses of irrigation water are restricted. Hence the increase in irrigation efficiency. Due to the reduction in percolation, salt leaching is less and the input of salts by the irrigation water begins to build up the soil salinity. The salinity reaches a maximum in year 9. Thereafter, it decreases again while simultaneously the irrigation application goes up and the efficiency down. Figure 5, which shows the non-irrigated area, may shed some light on this phenomenon.

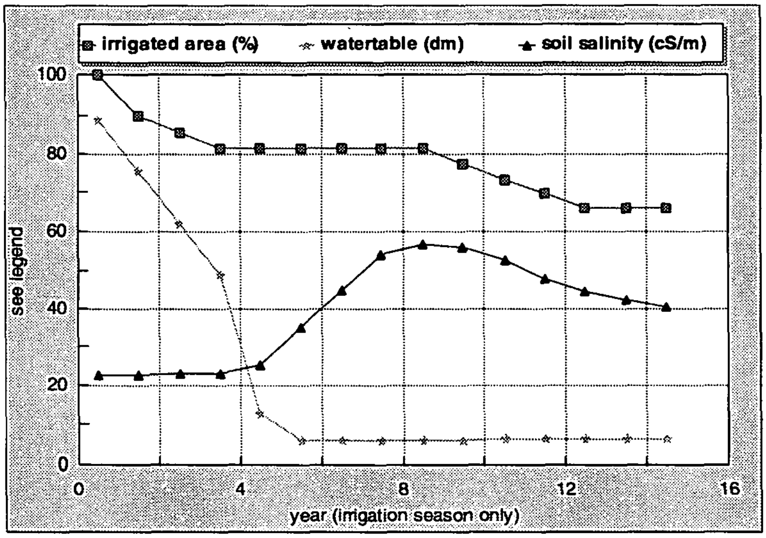

Figure 4. Interrelations between irrigated area, watertable depth and soil salinity

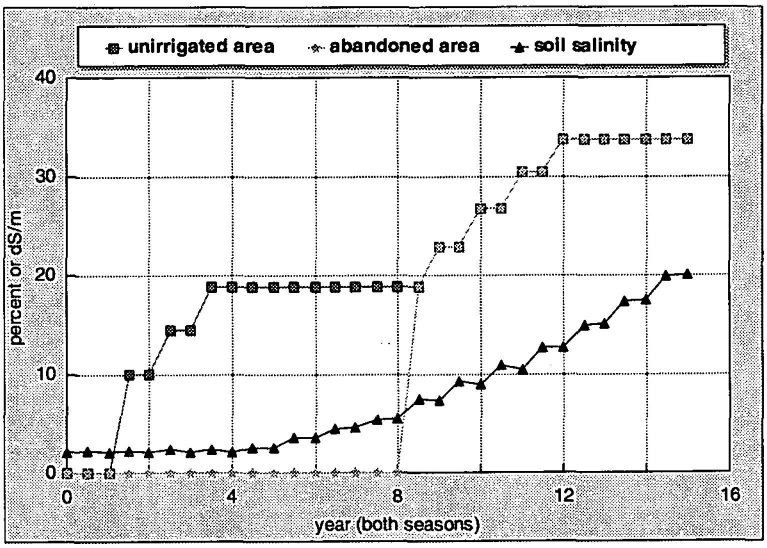

Figure 5. Changes in size of unirrigated area, abandoned area and soil salinity

The unirrigated (rotational fallow) area in Figure 5 increases from 0 to about 20% in the first four years. After this, the area remains constant until year 8. Thereafter, the fallow land increases again to more than 30%. This land becomes permanently fallow because it is abandoned. Its soil salinity reaches high values (20 dS/m). The abandoned area has a dry topsoil and groundwater is evaporated through capillary rise from the watertable. The area serves as a natural 'drain'. The salts brought in by the irrigation water accumulate here. The abandoned land permits drainage of the irrigated land. This explains why, in Figure 2, the irrigation application is increased after year 8, while the efficiency diminishes, and with it, the salinity (see Figure 4).

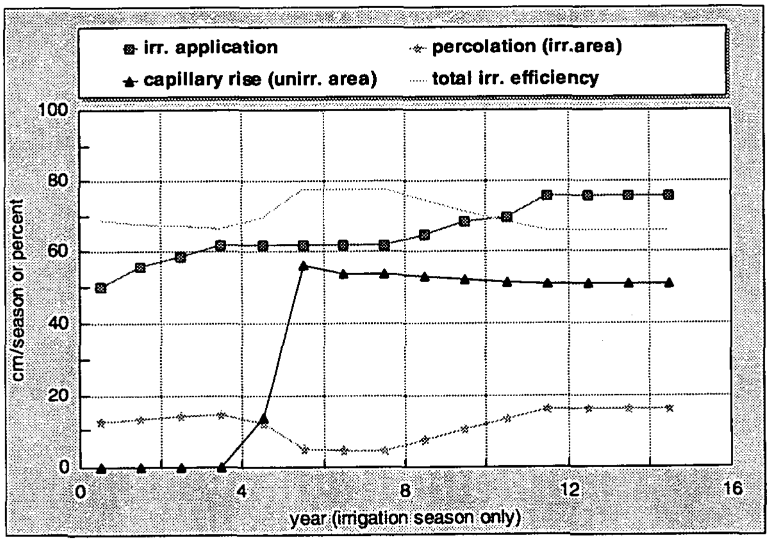

Figure 6. Changes in irrigation application, capillary rise, percolation and total irrigation efficiency

A summary of the variation of some hydrologic factors in time is given in Figure 6, showing stabilization at the end.

Conclusions

1. Irrigation and agricultural practices both determine the water and salt balance, which in turn determine these practices. There is a boomerang effect. All contributing factors are interwoven into a coherently knitted tissue.
2. Isolated drainage measures to combat problems of waterlogging and salinity run the risk of failure.
3. Hydro-agro-salinity models such as SALTMOD are a useful tool to understand the the intricate interrelations.

ILRI is developing a model that combines the SALTMOD program in different polygons with the SGMP[2] model for the flow of groundwater between the polygons: a Regional Salinity Model (RSM).

Discussion

The author explained that the graphs shown during the presentation (and reproduced in this paper (ed.)) were produced with a commercially available spreadsheet program, on the basis of output data from SALTMOD. The model produces a number of standard graphics, but they are not ideal for presentation. Results from the model were checked with field results, e.g. in Egypt, India, Pakistan and Portugal. Asked about farmers responses the author answered that SALTMOD can give three farmers responses. In practice when the watertable below a field rises, the farmer will reduce the irrigation application on that field. When the soil in a field becomes too saline, the farmer will abandon that field and concentrate available water on other fields. When water is scarce and the farmer does not have enough water available to irrigate all his fields, he will introduce fallow periods. If a user of SALTMOD selects the option *farmers response*, then the model (1) reduces applications on fields where the watertable rises too high, (2) abandons salinized fields and (3) introduces fallow periods when water is scarce. In answer to the last question, the author explained that SALTMOD was also applied on pilot areas in Mexico.

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[2] SGMP is a numerical groundwater model developed by ILRI. It is discussed further in Dr. Boonstra's contribution to these proceedings.

DRAINMOD-S AS AN INTEGRATED IRRIGATION AND DRAINAGE MANAGEMENT TOOL

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Introduction

FAO (1990) estimated the gross area of the world's irrigated land at 270 million hectares. During the past four decades, development of irrigated agriculture provided a major part of the increase in production necessary to meet population demands. About 36% of the total crop production came from less than 15% of the arable land that was irrigated. The FAO projections of expansion of irrigated land to the year 2000, based on previous trends modified by land, capital and inputs required to meet future needs, was 2.52% per year from 1984 to 2000. However, these projections are not likely to be met due to several reasons. Existing irrigation projects in several parts of the developing world are poorly performing due to poor operation and maintenance. Meanwhile about 20-30 million hectares are severely affected by salinity and an additional 60-80 million hectares are affected to some extent. Moreover, water resources in arid and semi-arid regions, where irrigation is necessary for crop production, are facing rapid decrease in the per capita share with increasing competition on water from other sectors (Engleman and LeRoy, 1993). The total area currently irrigated is about 235 million hectares.

Traditionally, irrigation and drainage systems were designed, constructed and managed separately. More often, irrigation systems were introduced without thinking about the drainage needs. Moreover, the classic design and management concepts depend on hypotheses that seldom exist in practices. Performance of such irrigation and drainage systems is often below expectation due to many unforeseen inter-relationships that were overlooked in the design or cannot be understood during the management stage. Because of the complexity of the soil-water-crop relationships, it was practically impossible to define their exact physical state and behavior. Therefore, in dealing with any particular problem, no other way was possible except simplifying the system by concentrating upon the factors which appear to have the greatest and most direct bearing upon the problem at hand. With more understanding of the state and movement of water in the soil, plant and atmosphere and with the concurrent development of experimental and computational techniques allowing more exact measurements and more complicated computation, a more holistic approach for addressing the problem became possible (Hillel, 1980a; Hillel, 1983).

In recent years computer simulation models that describe the performance of field scale water management systems have been developed. They are important and useful in simulating the mechanisms and processes governing movement of water and solutes in soils, handling a large number of variables and predicting actions and interactions of multiple processes over long periods of time. A good review of models based on different approaches is given by Skaggs (1992).

Water management in irrigated land

The objective of water management in irrigated agriculture is to maintain an adequate quantity of soil moisture available for plants at all times, and to leach salts out of the root zone before they build up to levels that might affect yield. In both cases, soil being the media for water and solute movement and crop yield being the target of irrigation, makes both plant and soil determinant factors in water management. Drainage is equally important for sustainable crop production otherwise salinity control will not be possible. The quality of irrigation water also is a major factor in management. Increasingly, more saline water is used in irrigation due to scarcity of fresh water resources.

Irrigation water supply and movement

Under arid and semi-arid climatic conditions, irrigation is necessary to provide the evaporative demands of field crops. The rate of water applied to the irrigated fields depends on many factors, among them are climatic conditions, water supply, crop type and growth stage; irrigation method and economics (Hansen et al., 1980 and Hillel, 1983). The quantity and frequency of irrigation are determined on the basis of these factors but in all cases they have to satisfy the crop water requirements at any given time through the different growing stages. Crop growth depends on the availability of moderate quantities of soil moisture in the root zone. However, excessive or deficient quantities of soil moisture cause reduction or even loss of the crop yield (Hiler, 1969). Therefore, the soil moisture content in the root zone should be maintained between an upper limit that ensures an adequate diffusion rate of oxygen to the roots and a lower limit which does not cause the plant to spend extra energy to meet its water requirements.

Generally, irrigation water is abstracted from a conveyance system, pipe or channel, and discharged onto a field sloping away from the point of supply. At the time of initiation of flow the soil is normally at a uniformly low soil moisture content. In surface irrigation, water moves down the slope as an advancing wave and infiltrates into the soil. As the wave progresses down the field, its magnitude is reduced by the water infiltrating into the soil until a point is reached where infiltration has accounted for the whole discharge, and there the advance terminates. In case the irrigation supply is more than adequate water may build-up on the field causing ponding conditions. If more water is still provided spills or surface runoff occurs.

The water infiltrating into the soil moves downward and laterally forming a wetting front. Infiltration is affected by soil factors such as hydraulic conductivity, initial soil moisture content, surface compaction, depth of profile and groundwater table depth. It also depends on climatic factors such as intensity, duration and time distribution of rainfall and temperature. Finally, plant factors such as extent of cover and depth of root zone also influence the infiltration of water into the soil. The amount of water infiltrating into a unit surface area of soil may be computed from a water balance at the soil surface during certain time increment Δt. The balance equation may be written as:

$$F = I - RO - \Delta W \tag{1}$$

where F is infiltration (cm), I is irrigation (cm), RO is surface runoff (cm) and ΔW is the change of water stored on the surface during the time interval Δt. Approximate equations such as the Green-Ampt equation (Hillel, 1980) can be used for estimating the infiltration rate. Until all irrigation water on the soil surface infiltrates into the soil, the direction of water movement is essentially downwards. While water is moving downward, it fills the soil pores of the unsaturated zones until the soil moisture content increases up to its field capacity. Excess water continues moving downwards repeating this process until the remaining volume reaches the groundwater table causing a rise in its levels.

Water is removed from the soil by the plant roots or by direct evaporation from the soil surface. Shallow-rooted crops will require more frequent irrigation than deep-rooted crops. Similarly, the same crop requires more frequent irrigation in the early stages than when its roots develop to its full depth. The combined effect of plant transpiration of water to the atmosphere through their leaves and the water evaporation directly from the soil is the evapotranspiration (*ET*) of the crop cover. A plant in wet soil will extract more water than the same plant growing in dryer soil. The evapotranspiration reaches its full potential rate for a given set of climatic conditions when the soil is well-watered and the crop completely shades the soil surface (Walker and Skogerboe, 1987). Potential *ET* depends on climatological factors which include net radiation, temperature, humidity and wind velocity. However, the actual field evapotranspiration is often limited by soil moisture conditions and is less than the potential evapotranspiration. When the available soil moisture in the root zone is depleted, the *ET* can not exceed the upward flux from the groundwater table. After the end of infiltration and between two successive irrigation the water movement above the watertable remains in upward direction. The upward flux by capillary water movement increases with a shallower watertable than from a deeper one. Hence, a shallow groundwater table can effectively contribute in meeting the crop evaporative demands through upward capillary flow.

Water that percolates below the root zone has no direct value for the crop. When it reaches the groundwater table, the later rises proportionally to the quantity of water entering the watertable: in general the watertable should not rise and remain in the root zone. The soil in the root zone should be well aerated by the continuous exchange of oxygen and carbon dioxide between the air-filled pores and the external atmosphere. Most terrestrial plants cannot transfer oxygen from their aerial parts to their roots at a rate sufficient for root respiration. Thus, an excessive wet soil will stifle the crop roots. In many irrigated lands, natural drainage is not sufficient to lower the groundwater table at an adequate rate for optimal crop cultivation. In this case drains should be constructed to provide the required rate of groundwater table drawdown. The rate of subsurface water movement into drain tubes or ditches depends on the hydraulic conductivity of the soil, drain spacing and depth, drain capacity, profile depth and groundwater table height above the drain. The change in air volume in a thin section of soil of unit surface area which extends from the soil surface to the impermeable layer and is located midway between adjacent drains (Fig. 1) is given by the following balance equation (Skaggs, 1978):

$$\Delta V_a = D + ET + DS - F \qquad (2)$$

where ΔV_a is the change in the air volume (cm), D is the artificial lateral drainage from the section, ET is the evapotranspiration (cm), DS is the deep seepage, if any (cm) and F is the infiltration (cm) entering the section during the time increment Δt.

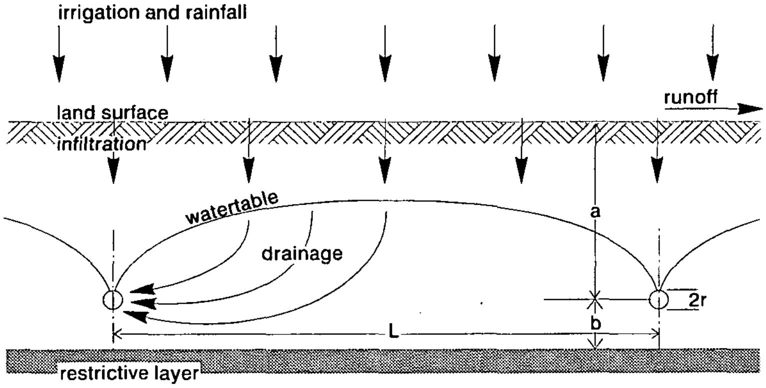

Figure 1. Schematic diagram of water management system with subsurface drains

Salt movement and salinity control

Irrigation water from streams, rivers and groundwater contains significant quantities of dissolved salts. Applying 100 cm of water which is a normal quantity in a season, with salt content of 300 mg/liter means adding 3 tons of salt per hectare to the irrigated land. Irrigation water during its residence in the soil tends to dissolve additional salts. As it moves through the profile, soil moisture carries its solute load in its convective stream, leaving some of it which is adsorbed, taken up by plants, or precipitated whenever their concentration exceeds their solubility (Hillel, 1980). Solutes move not only with soil moisture, but also within it in response to concentration gradients. At the same time, solutes react among themselves and interact with the solid matrix of the soil in a continuous cyclic succession of interrelated physical and chemical processes.

While upward flow from a groundwater table is an important source of water for transpiring plants, it is also a cause of salt accumulation in the root zone. Although the rate of upward movement of water from a groundwater table may not be sufficient for plant growth, it may be rapid enough to present a serious salinity hazard especially when the groundwater is saline (Gardner, 1960). The salinization hazard may still exist even when the groundwater table is several meters below the soil surface. In many irrigation projects, under-irrigation with the consequent salinization of the soil profile due to capillary rise is almost inevitable if preventive measures are not taken. Salinization may be aggravated by over-irrigation which causes a rise of the groundwater table and hence accelerates the upward flow.

The salt balance is a summary of the quantities of salt inputs and outputs for a defined volume or depth of soil during a specified period of time. If salts are neither generated nor decomposed chemically during the movement of the soil solute, then the difference between the total input and output must equal the change in salt content of the soil zone considered. The salt balance can be used as an indicator of salinity trends and the need for salinity control measures in irrigation schemes. The salt balance equation for a thin soil section extending from the soil surface to the bottom of the root zone and of unit surface area during a time increment Δt is given by the following equation (van der Molen, 1983):

$$\Delta S = F.C_i - R.C_d \qquad (3)$$

where ΔS is the change in salt content of the root zone in meq/m^2, F is the net volume of water infiltrated into the soil as a result of irrigation and rainfall (cm) during the time interval Δt, R is the net volume of water moving across the lower boundary of the root zone (cm) as a result of deep percolation and upward flux during the time interval Δt; C_i is the salt concentration (meq/liter) in the irrigation water and C_d is the salt concentration (meq/liter) of the soil moisture below the root zone. Equation 3 can be expressed in terms of the electric conductivity of the saturated paste, EC_e which is roughly proportional to the concentration C. Equation 3 implies that a net downward movement, i.e. deep percolation below the root zone more than upward flow, is required to reduce the salt accumulation in the root zone. At a state of salt equilibrium (i.e. $\Delta S=0$) the salt added equals the salt removed.

An excessive accumulation of salts in the soil profile causes a decline in productivity. Soil salinity affects plants directly by reducing the osmotic potential of the soil solution and by the toxicity of specific ions such as boron, chloride and sodium. Some plants can survive in salt affected soil but many are affected to varying extent depending on their tolerance to salinity. Even, the same crop has different tolerance levels to salinity for its different growing stages. Mass and Hoffman (1977) indicate that each increase in soil salinity (electric conductivity of the saturated paste) in excess of the concentrations that initially begin to affect yield will cause a proportional decrease in yield. They have proposed the following equation to express this effect:

$$RY = 100 - b\,(EC_e - a) \tag{4}$$

where RY is the relative crop yield (%), EC_e is the salinity of the soil saturated extract (dS/m), a is the salinity threshold value for the crop representing the maximum EC_e at which a 100% yield can be obtained (dS/m) and b is the yield decrement per unit of salinity, or % yield loss per unit of salinity (EC_e) between the threshold value (a) and the EC_e value representing the 100% yield decrement. The threshold value depends on the crop tolerance to salinity. The relative salt tolerance of most agricultural crops is well known. General salt tolerance guidelines are given by most of the irrigation text books (FAO, 1985; Hansen et al., 1980).

The leaching of excess salts from the root zone is an essential aspect of salinity control. Without leaching, salt will accumulate in direct proportion to the amount of water applied and its salt content. Salt residues can be prevented from accumulating during repeated irrigation-evapotranspiration cycles by applying water in an amount greater than evapotranspiration. This practice will cause a significant fraction of applied water to flow through - and past - the root zone and leach away the excess salts. However, unless the groundwater table is very deep or subsurface drainage is sufficiently rapid, the excess irrigation causes a progressive rise of the watertable. Once, the watertable comes closer to the soil surface between irrigations the groundwater tends to flow upwards into the root zone by capillary action.

The leaching requirement depends on the irrigation water salinity and the crop tolerance to soil salinity. FAO (1985) recommends the equation proposed by Rhoades and Merrill in 1976 to calculate the leaching requirements for ordinary surface irrigation methods. The equation reads:

$$LR = \frac{EC_i}{5EC_e - EC_i} \tag{5}$$

where LR is the minimum leaching requirement (dimensionless fraction) needed to control salts within the salinity tolerance level of a certain crop which is EC_e (dS/m) and EC_i is the salinity of the applied irrigation water (dS/m). The total depth of water that needs to be applied to meet both the crop demand and the leaching required can be estimated from the following equation:

$$I = \frac{ET}{1 - LR} \tag{6}$$

where I is the irrigation water depth (cm), ET is the crop evapotranspiration (cm), and LR is the leaching fraction (ratio).

Theoritically speaking, the timing of leaching is of no significance provided crop tolerance is not exceeded for extended or critical periods of time. Salt takes time to accumulate in the root zone of initially non-saline soils, to a concentration that reduces yield. Leaching can be done at each irrigation, every second irrigation or less frequently such as seasonally or at even longer intervals. In many instances, the usual inefficiencies of irrigation water application satisfy the leaching requirement, particularly with good quality irrigation. water. In the case of irrigation with more saline water, larger amounts of water will be needed to meet the leaching requirement. When the leaching fraction exceeds 0.25 -0.3, it may be more efficient from a water saving point of view to change to a more tolerant crop or to accept a relative yield less than 100% of the potential.

Water management modeling

Background

The field scale water management simulation model DRAINMOD is developed and field tested under varying conditions (Skaggs, 1978; Skaggs, 1982). It uses functional algorithms to approximate the hydrologic components of shallow watertable soils. Approximate methods are used to simulate surface runoff, infiltration, drainage, upward flow, evapotranspiration, and seepage processes on hour-by-hour, day-by-day basis. Input data include soil properties, crop parameters, drainage system parameters, climatological and irrigation data. DRAINMOD is based on solving water balances similar to those described by Equations 1 and 2. The basic time increment used in both equations is 1 hour. However, when rainfall does not occur and drainage and ET rates are so low that the groundwater table position moves slowly with time, a Δt of 1 day is used in Equation 2. Conversely, time increments of 0.05h are used to compute the infiltration when rainfall rates exceed the infiltration capacity.

The basic water balance equation for the soil profile (Eq. 2) does not require knowledge of the distribution of the soil moisture content within the profile. However, the methods used to evaluate the individual components such as drainage and ET depend on the position of the watertable and the soil moisture distribution in the unsaturated zone. Groundwater table depth is determined in DRAINMOD at the end of every water balance calculation. The pressure head distribution above the groundwater table during drainage is assumed nearly hydrostatic. The soil moisture distribution under these conditions is the same as in a column of soil drained to equilibrium with a static watertable. These assumptions will generally hold for conditions in which the Dupuit-Forchheimer assumptions are valid, i.e. for situations where the ratio of the drain spacing to profile depth is large. The maximum groundwater table depth for which the approximation of a drained to equilibrium soil moisture content distribution will hold depends on the hydraulic conductivity functions of the profile layers and the *ET* rate.

The determination of *ET* is a two-step process in the model. In the first step, the daily potential evapotranspiration (*PET*) is calculated in terms of atmospheric data and is distributed on an hourly basis for 12 hours representing the day time (6 am to 6 pm). In case of rainfall, hourly *PET* is set equal to zero for any hour in which rainfall occurs. In the second step, a check is made to determine whether *ET* is limited by soil moisture conditions. If the soil moisture conditions are not limiting, *ET* is set equal to *PET*. This water can be supplied by soil moisture stored in the root zone if it has not already been used, down to a lower limit (wilting point or a higher water content if desired). This deficit will be compensated fully or partly by upward flow from the groundwater table depending on its depth at the beginning of the time step. The watertable will accordingly drop to a new position as a result of the upward flow. When the soil moisture content in the root zone is depleted to the set lower limit, *ET* is limited by soil moisture conditions and is set equal to the upward water movement.

The effective root depth is used in DRAINMOD to define the zone from which water can be removed as necessary to supply *ET* demands. An effective root depth is defined for all periods considered in the simulation process. When the soil is fallow, the effective root depth is defined as the depth of the thin layer that will dry out at the surface. The rooting depth function for each crop included in the simulation is read in as a table of effective root depth versus Julian date. Among many other factors influencing root growth and distribution, soil moisture is the most important. This includes both depth and fluctuation of the groundwater table as well as the distribution of soil moisture during dry periods.

Procedures used in DRAINMOD to calculate drainage rates assume that lateral water movement occurs mainly in the saturated zone below the groundwater table. The lateral flux is evaluated in terms of the watertable elevation midway between drains and the water level in the drain. The model uses the Hooghoudt steady state equation to calculate the drainage rates. Although this equation was derived for steady state conditions, it compares well with transient methods for predicting drainage flux when applied sequentially for short time increments or for small changes in the groundwater table position. Thus the new position of the watertable at the end of each time increment is determined on the basis of the upward flux and the lateral drainage during this particular time increment.

The overall objective of agricultural water management systems is mostly to eliminate water related factors that limit crop production or to reduce those factors to acceptable levels. The objective functions considered by DRAINMOD are the number of working days which characterize the ability of the water management system to insure trafficable conditions during specified periods, the sum of excess water at depths less than 30 cm that provides a measure of excessive soil moisture conditions during the growing season, sum of dry days during a growing season which quantifies the length of time when deficient soil moisture conditions exist. Groundwater table position and factors such as the *ET* deficit are used to quantify stresses due to excessive and deficient soil moisture conditions. Stress-day-index methods (Hiler, 1969) are used to predict relative yields as affected by excessive soil moisture, deficit or drought conditions and planting date delay. The following algorithms are examples used for corn:

$$RY_w = 100 - 0.71\ SDI_w \tag{7}$$

$$RY_d = 100 - 1.22\ SDI_d \tag{8}$$

where RY_w and RY_d are the relative yields if wet stress and dry stress occurred, and SDI_w and SDI_d are the stress-day-index for excessively wet conditions and the stress-day-index for drought conditions, respectively. The overall response of the crop to delayed planting date, excessive wet and dry conditions can be determined as follows:

$$RY = RY_p \times RY_w \times RY_d \tag{9}$$

where RY is the overall relative yield, RY_p the relative yield for delayed planting and RY_w and RY_d are as defined above.

The simulation model DRAINMOD as briefly presented above, is best suited to humid regions although it may also be applied to irrigated conditions where irrigation applications may be introduced in a similar way as rainfall. However, the model can not simulate the solute movement nor it can predict the salt distribution and its changes in the soil profile.

The reliability of DRAINMOD for irrigated crop land in a semi-arid climate was tested by Chang et al. (1983) with field data from California. Groundwater table elevations predicted by the model reasonbly agreed with measurements for five experimental locations differing in soil texture. The first successful attempt made to test the reliability of the model to simulate water management in irrigated arid land was made by Abdel-Dayem and Skaggs (1990). Outputs of the DRAINMOD simulation were used in a spread-sheet analysis of the corresponding salt balance computed on daily basis. The results agreed well with field data about soil salinity changes measured at the beginning and the end of the crop season in the Nile Delta. This encouraged research to proceed for developing a new version of DRAINMOD that combines simulation of both soil moisture and solute movement in the soil profile in irrigated land with a shallow groundwater table and provided with horizontal drains.

Model development

The development of a salinity version of DRAINMOD (= DRAINMOD-S) started by modifying the model DRAINMOD to provide daily average fluxes as a function of depth in the unsaturated zone above the groundwater table (Kandil et al., 1992; Kandil, 1992). The average flux over time step Δt at any distance Z below the soil surface is determined by breaking the profile into depth increments, Δz (Fig. 2) and calculating the volume of water removed or added to each increment. In the saturated zone, the vertical fluxes are linearly decreased from the net recharge at the watertable level to zero at the impermeable layer depth. In addition, a profile of soil moisture content is also generated using soil moisture characteristic data based on the drained to equilibrium assumption. This method proved to give reliable results for flux computation (Skaggs et al., 1991) and solute transport (Kandil et al., 1992) when compared to fluxes predicted with a finite element solution of the Richards equation.

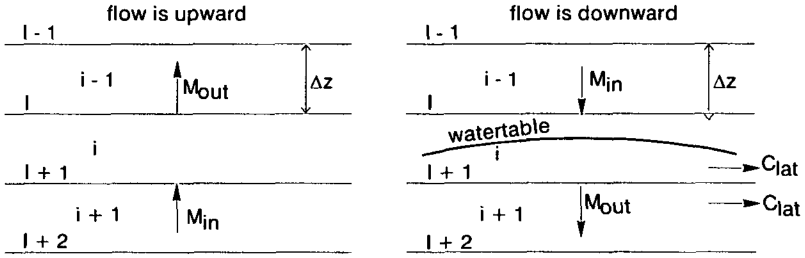

Figure 2. Schematic diagram of flow field in the soil profile considered in DRAINMOD-S

Kandil (1991) used a mass balance approach to solve the advective-dispersive-reactive equation for total dissolved salt concentrations in the soil profile at each time step. The basic differential equation reads:

$$\frac{\partial \theta C}{\partial t} = \nabla \cdot (\theta D_h \cdot \nabla C - qC) + R(C) + \Gamma_c \qquad (10)$$

where C is the volume-average solute concentration (mg/liter), θ is the volumetric soil moisture content (cm^3/cm^3), t is the time (day), D_h is the second-rank hydrodynamic dispersion coefficient (cm^2/day), q is a flux vector (cm/day), $R(C)$ is a general solute reaction term (mg/liter.day) and Γ_c represents the solute sources (mg/liter.day). For one-dimensional systems composed of non-reactive solutes, Equation 10 reads:

$$\frac{\partial \theta C}{\partial t} = \frac{\partial}{\partial z}\left(\theta D_{hz} \frac{\partial C}{\partial z}\right) - q_z \frac{\partial C}{\partial z} + \Gamma_c \qquad (11)$$

where D_{hz} is the hydrodynamic dispersion coefficient in the vertical direction, and q_z is the flux. The equation can be approximated for downward flow as:

$$C_{ini} = \frac{C_{io}\,\theta_{io}}{\theta_{ini}} + \frac{M_o - M_i}{\Delta Z\,\theta_{ini}} + \frac{\Gamma\,\Delta t}{\theta_{ini}} \qquad (12)$$

where C_{io} and C_{in} are the salt concentrations at the end of the pervious and the new time steps (mg/liter); θ_{io} and θ_{in} are the soil moisture contents of layer i at the end of the previous and the new time steps; M_i and M_o are the mass of salt (mg) entering and leaving the soil layer i in time Δt; Γ is a source/sink term (mg/liter.day); ΔZ is the vertical distance increment (cm); and Δt is the time increment (day).

For upward flow with no drainage and no lateral water movement, the advective-dispersive-reactive equation is approximated by changing the sign of the second term on the left side of Equation 12 to a negative sign and the expressions for calculating M_o and M_i will be adjusted for the flow conditions accordingly. During periods where evapotranspiration exceeds the infiltration rate, the salt was assumed to leave the soil with a net flux at soil surface and added as a source term to the root zone. A source-sink term is used in terms of total salinity rather than individual salt species. Precipitation and dissolution of salts are considered by defining a concentration level of the soil solution at which there is no precipitation and no dissolution. Site specific values of this concentration levels can be determined using the geochemical assessment model for environmental systems MINTEQA2 (USEPA, 1991).

The solute transport model is coupled with DRAINMOD through independent or alternate solution methods. The combined model is called DRAINMOD-S. The additional inputs are the salinity of the irrigation water and the initial solute concentration in the soil profile. For independent flow and transport models the flow model is first solved for the entire duration of the simulation and results are stored. The results are then used to solve the transport model. For an alternate solution method, the flow and transport models are solved alternately over a series of time steps that together constitute the simulation period. In both cases, DRAINMOD is used to predict groundwater table depth, drainage rate, soil moisture fluxes and soil moisture contents. Then concentrations are predicted by the transport model. Computational requirements are similar for both approaches. Additional outputs other than those computed by DRAINMOD are predictions for solute concentration as a function of profile depth and time and drainage water salinity as a function of time.

The above approximate solution for solute transport based on mass balance was compared with a more accurate approach based on finite element solution developed by the same author (Kandil et al., 1992). The comparison was made for two soils, namely clay and sandy loam. The results of both methods were reasonably in agreement with a correlation coefficient $R^2 = 0.82$. However, the mass balance-based approach was two orders of magnitude faster than the finite element based approach. The mass balance approach is therefore considered reliable, simple, significantly saving simulation running time and will not deal with convergence and stability problems that sometimes arise with numerical solutions to nonlinear differential equations.

The response of crop yield to soil salinity is determined by Equation 4. The overall crop response model for DRAINMOD-S is modified to read:

$$RY = RY_p \times RY_w \times RY_d \times RY_s \qquad (13)$$

where Equation 13 is similar to Equation 9 but with the right side multiplied by the relative yield due to salinity stress, RY_s. To compare predicted yields to field measured yields, relative yield may be expressed as:

$$RY_{measured} = \frac{Y}{Y_o} \qquad (14)$$

where Y is the measured or observed yield in a given year and Y_o is the long-term average yield that would result from a combination of abundant irrigation, good drainage, root zone salinity below the threshold value and favorable crop production inputs.

Model testing

The reliability of the DRAINMOD-S for simulating water management in irrigated lands under actual field conditions was tested against data sets from the Zankalon Experimental Field (ZEF) in the Nile Delta (Kandil et al., 1992b). The soil profile consists of alluvial clay extending to a considerable depth below surface. The ZEF is provided with covered drains at a spacing of 20 meters and depth of 1.2 m approximately. Soil properties are represented by the saturated hydraulic conductivity and soil moisture characteristics. The later were used for determining the drained volume, unsaturated hydraulic conductivity, coefficients of Green-Ampt infiltration equation and rate of upward movement as a function of groundwater table depth using the SOILPREP program developed for preparing soil input data sets for DRAIMOD (Workman et al., 1990). Climate, groundwater table depth, drain discharges and irrigation water quantities and their salinities, crop data and soil salinities for 15 cm increments of the soil profile down to 150 cm below the soil surface are available for the cropping seasons 1989 - 1991.

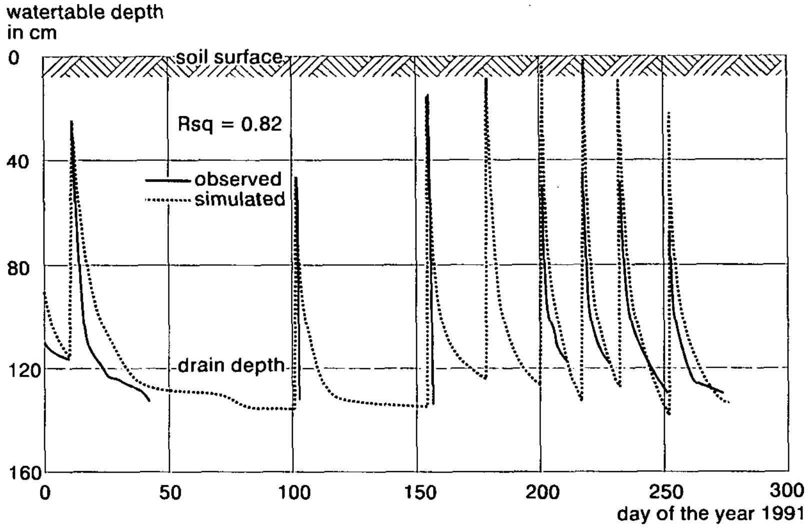

Figure 3. Comparison between the simulated measured daily groundwater table depths midway between laterals for the Zankalon Pilot Area

A sample of measured and predicted groundwater table depths midway between two lateral drains is shown in Figure 3. The agreement between predicted and measured values was quantified by conducting a regression analysis. The correlation coefficient (R^2) was in the range of 0.80 - 0.88 for all the tested data sets. There was also good agreement between the simulated and the measured drainage rates. The average of measured salt concentrations in three layers versus simulated values, as a function of time, are shown in Figure 4. The trend

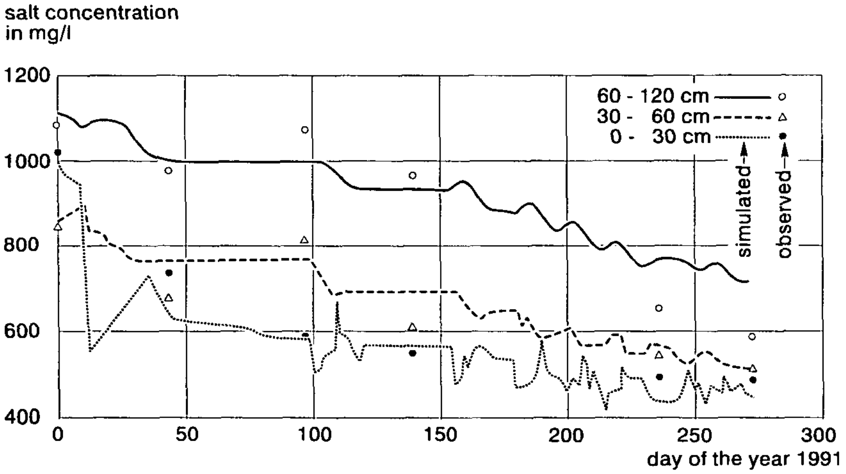

Figure 4. Comparison between the average measured and the simulated soil salinity at different depths as function of Julian days

of the simulated salt concentrations in Figure 4 mirrors the net infiltration, buffered by depth below soil surface. The results indicate that the effect of irrigation salt concentration on the soil salinity is more pronounced in the surface layer than in the deeper layers. The differences become less as time progresses, until the soil salinity is reduced to almost the same level as the irrigation water salinity irrespective of its initial salinity. A good agreement was also observed between the simulated and the measured drain effluent salinity.

DRAINMOD-S was also tested under semi-arid conditions in India (Merz, 1996). The study was carried out using data from the RAJAD Project in the Chamball Command Area near Kota, Rajasthan. Simulated water management in wheat and soybean fields showed that predicted and measured groundwater table depths were in reasonable agreement. The same was also noticed with the seasonal long term salinity trends.

Model applications

DRAINMOD-S as described above can be used either for the design of a new drainage system that should fulfill certain objectives or for evaluating the performance of existing drainage systems and their short and long term impacts on the groundwater table, soil salinity and crop yield. It can also be used for testing different water management strategies involving water quality and economic issues.

For design purposes, drain depth and drain spacing can be determined for a given set of conditions in an irrigated area. These conditions are represented by irrigation practices, quality of irrigation water, soil physical properties, initial salinity distribution in the soil profile, climatic data, crop rotation and other general information such as the drain radius and depth to impermeable layer. Overall relative crop yield is then computed for a range of drain spacings. A graph showing the relationship between the drain spacing and relative yield will give the drain spacing corresponding to the maximum crop yield (Figure 5). It is the drain

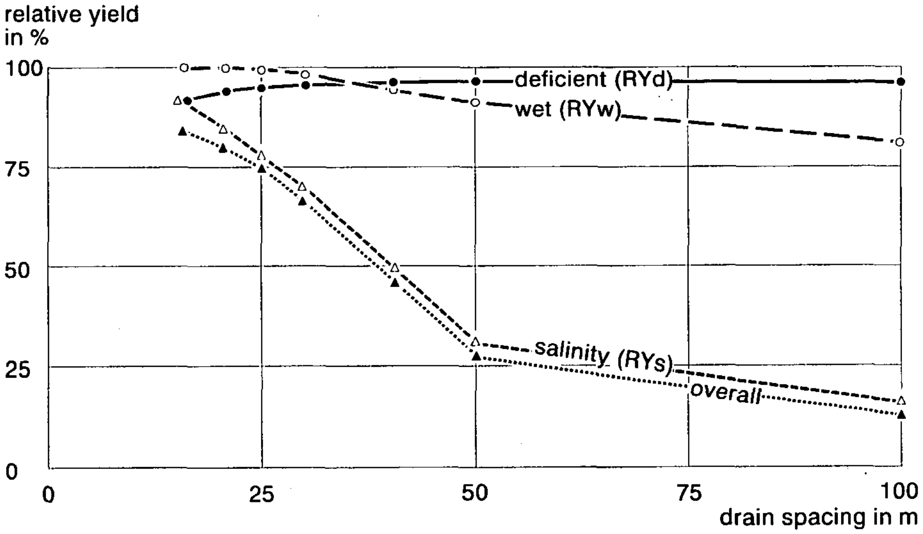

Figure 5. Relative crop yield as a function of drain spacing

spacing that, for the given set of input data, results into minimum stresses due to excessive wetting, drought, and soil salinity. Where there is more than one crop in the crop rotation, it is possible to have different drain spacings that produce the maximum yield of each crop. In this case, the designer has to assess the performance through either adjusting the irrigation practices of some crops in the rotation to eliminate stresses caused by the irrigation inputs (if possible) or selecting the spacing on the basis of economic analysis (costs and benefits). Market prices of crops and interest rates play an important role in the latter case.

Kandil et al. (1993) compared the performance of several drainage and irrigation strategies in an area, where a crop rotation consisting of bean, maize, wheat, cotton and soybean was proposed. In this study, different drain depths and drain spacings were considered as well as different timing of irrigation water applications and different leaching fractions. The timing of adding leaching water was also considered. DRAINMOD-S was used to simulate the water management for each individual case over a 19 year-period. The relative yield was predicted for each crop which was grown several times during this period. Beans, which is a salt sensitive crop, responded well to additional leaching water applied before the beginning and at the middle of the growing season. It gave maximum yield with closer drain spacing and less frequent irrigation. On the other hand, maize yield was maximum at wider drain spacing and more frequent irrigations. Wheat and soybean are less sensitive to salinity in the soil and therefore high yields were obtained at wider spacings. All crops responded well to pre-cropping leaching rather than to an uniformly distributed leaching fraction with each irrigation. Deeper drains were generally more effective in reducing salinity stresses and in increasing crop yields.

El-Hawary (1995) presented an approach for the determination of the most economic design of subsurface drainage projects based on the results of water management simulation using DRAINMOD-S. The calculated crop yields over the project life time for different drain depths and spacings were used for economic analysis based on the net present worth of each design. An interesting conclusion was that the most economic design is not necessarily the one producing maximum yield. The analysis showed that it is most sensitive to the interest rate rather than to initial project costs or crop price changes.

References

Abdel-Dayem, M.S. and Skaggs, R.W., 1990. Extension of DRAINMOD for Simulating Water Management in Arid Regions. Symposium on Land Drainage for Salinity Control in Arid and Semi-Arid Regions, Cairo, Egypt.

Chang, A.C., Skaggs, R.W., Hermsmeier, L.F. and Johnston, W.R., 1983. Evaluation of a Water Management Model for Irrigated Agriculture. Transactions of ASAE, Vol. 26, No. 2, pp 412-418 and 422.

El-Hawary, A.M., 1995. Subsurface Drainage Design to Maximize the System Net Present Worth. Master Thesis, Department of Irrigation and Hydraulics, Faculty of Engineering, Cairo University, Egypt.

Engleman, R. and LeRoy, P. 1993. Sustaining Water: Population and the Future of Renewable Water Supplies. Population and Environment Program, Population Action International, USA.

FAO, 1985. Water Quality for Agriculture. Irrigation and Drainage Paper 29 (Rev. 1), Food and Agriculture Organization of the United Nations, Rome.

Gardiner, W.R., 1960. Soil Water Relations in arid and semi-arid conditions. UNESCO 15, pp 37-61.

Hansen, V.E., Israelsen, O.W., and Stringham, G.E., 1980. Irrigation Principles and Practices. Forth Edition, John Wiley & Sons, New York.

Hiler, E.A., 1969. *Quantitative Evaluation of Crop Drainage Requirements.* Transactions of ASAE, Vol.12, No. 3, pp. 490-505.

Hillel, D., 1980a. Applications of Soil Physics. Academic Press, New York.

Hillel, D., 1980b. Fundamentals of Soil Physics. Academic Press, New York.

Hillel, D., 1983. Advances in Irrigation. Volume 2, Academic Press, New York.

Kandil, H.M., 1992. DRAINMOD-S: A Water Management Model for Irrigated Arid Lands. Ph.D. Thesis, North Carolina State University, N.C., pp 207.

Kandil, H.M., Miller, C.T. and Skaggs, R.W., 1992. Modeling Long Term Solute Transport in Drained Unsaturated Zones. Water Resources Research, Vol. 28, No. 10, pp 2799-2809.

Kandil, H.M., Skaggs, R.W., Abdel-Dayem, M.S., Aiad, Y. and Gilliam, J.W., 1992. DRAINMOD-S: Water Management Model for Irrigated Arid Lands, 1. Theories and Tests. ASAE Winter Meeting, Paper No. 922566, Nashville, Tennessee.

Kandil, H.M., Skaggs, R.W., Abdel-Dayem, M.S., Aiad, Y. and Gilliam, J.W., 1993. DRAINMOD-S: Water Management Model for Irrigated Arid Lands, 2. Crop Yield and Applications. Workshop on Subsurface Drainage Simulation Models, 15th International Congress of ICID, The Netherlands.

Mass, E.V., and Hoffman, G.J., 1977. Crop Salt Tolerance: Current Assessment. Journal of Irrigation and Drainage Division, ASCE 104 (IR2): 115-134.

Merz, R.D., 1996. Application of DRAINMOD-S to Irrigated Semi-Arid Land in India. Master Thesis, Department of Biological and Agricultural Engineering, North Carolina State University, N.C., Raleigh.

Molen, W.H. van der, 1983. Salt Balance and Leaching Requirement. Drainage Principles and Applications, Publication 16, Vol. 11, pp 62-100.

Skaggs, R.W., 1978. A Water Management Model for Shallow Water Table Soils. Water Resources Research Institute, Report No. 134, University of North Carolina, N.C. pp. 78.

Skaggs, R.W. 1982. Field Evaluation of a Water Management Simulation Model. Transactions of ASAE, Vol., 25, No. 3, pp 666-674.

Skaggs, R.W., 1992. Drainage and Water Management Modeling Technology. Proceedings of the Sixth International Drainage Symposium. Drainage and Water Table Control, Nashville, Tennessee, pp 1-11.

Skaggs, R.W., Karvonen, T and Kandil, H.M., 1991. Predicting soil water flux in drained lands. ASAE International Summer Meeting, Albuquerque, NM.

U.S. EPA, 1991. MINTEQ A1 / PRODEF A2. A Geochemical Assessment Model for Environmental Systems: Version 3.0 User's Manual, Center of Exposure Assessment Modeling (CEAM), U.S. Environmental Protection Agency, Georgia.

Walker, W.R. and Skogerboe, G.V., 1987. Surface Irrigation Theory and Practices. Prentice-Hall, Inc., New Jersey.

Withers, B. and Vipond, S., 1974. Irrigation: Design and Practice. B.T. Batsford Limited, UK.

Workman, S.R. and Skaggs R.W., 1990. PREFLO: A Water Management Model Capable of Simulating Preferential Flow. ASAE, 33(6), pp 1939 - 1984.

Discussion

During the discussion the author explained that hydrological parameters such as hydraulic conductivity vary in space and the applied drain spacing also varies. The maximum yield is obtained at a spacing of 20 m, but the most economic system is obtained at spacing 35 m. A participant asked about a sensitivity analysis and different production functions and the author explained that verification on crop yields had been done in the United States but not in Egypt.