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A holistic generic integrated approach for irrigation, crop and field management: the SALTMED model

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Abstract

A successful water management scheme for irrigated crops requires an integrated approach that accounts for water, crop, soil and field management. Most existing models are designed for a specific irrigation system, specific process such as water and solute movement, infiltration, leaching or water uptake by plant roots or a combination of them. There is a shortage in models of a generic nature, models that can be used for a variety of irrigation systems, soil types, soil stratifications, crops and trees, water management strategies (blending or cyclic), leaching requirements and water quality. SALTMED model has been developed for such generic applications. The model employs established water and solute transport, evapotranspiration and crop water uptake equations. In this paper, the model has been run with five examples of applications for one growing season using data from the literature. The model successfully illustrated the effect of the irrigation system, the soil type, the salinity level of irrigation water on soil moisture and salinity distribution, leaching requirements, and crop yield in all cases. Due to the scarcity of data sets that are suitable for model testing over the complete growing season, where different processes are acting simultaneously, a follow up paper will show the results of the model tests using data being collected from two sites in Egypt and in Syria as a part of ongoing SALTMED project.

Keywords: Model; Irrigation; Evapotranspiration; Salinity; Soil moisture; Crop growth; Yield; Water uptake; Water requirements; Leaching; Management; Integrated holistic generic approach

1. Introduction

The continuous increase in the earth's population requires more water for domestic, industrial, environmental, recreational and agricultural needs. More water to irrigate crops for food and fibre production for the expanding population is required. The increasing demand for water requires more intensive management of water resources and water conservation. Increasing demands for irrigation water while water resources are limited must ultimately lead to reuse and recycling of the available water resources (Bouwer, 1994; De Jager et al., 1997; Ragab, 1997). This is happening already in many parts of the world in both developed and developing countries, where field drainage and industrial and domestic wastewaters are reused and recycled for irrigation.

In applying saline/brackish water for irrigation, one should adopt an integrated approach which should account for soil, crop and water management at the same time. The approach should consider: (i) soil hydraulic properties/infiltrability, which affects water and solute movement; (ii) crop salt tolerance levels at various stages, selection of the most tolerant crop and application of highly saline water during the less sensitive stage is crucial; (iii) applying the appropriate water management strategy, blending with fresh water or alternative use of fresh water at the most sensitive stage and the saline one for the less sensitive stages (Rhodes et al., 1992); (iv) selecting the most appropriate irrigation system (Ragab, 1983, 1997) and (v) conducting a proper calculation of crop and leaching water requirements which are essential for water saving, controlling water table level, controlling drainage volume, and of course the final yield. There are a number of issues related to such an integrated approach. These issues are relevant to management, the environment and to the long-term effect on soils. More details are given by Hoffman et al.

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(1990), Oster (1994), Maas (1986), Shalhevet (1994), Yeo et al. (1997) and Ragab (1997, 1998).

Most existing models are single-process, oriented, e.g: (i) models for infiltration (Bresler, 1975; Vogel and Hopmans, 1992; Ragab et al., 1984; Fletcher Armstrong and Wilson, 1983); (ii) models for root water uptake (Cardon and Letey, 1992a; Coelho and Dani 1996); (iii) models for leaching or water and solute transport (Addiscott and Whitemore, 1991; Wagenet and Hutson, 1989; Cardon and Letey, 1992b; Kamra et al., 1991; Logan, 1996) or (iv) models for specific applications, i.e. certain irrigation system, soils, region or a crop (Šimůnek and Suarez, 1994; Magnusson and Ben Asher, 1990; Ragab et al., 1990; Noborio et al., 1996; Minhas and Gupta, 1993; Nour El-Din et al., 1987; Cardon and Letey, 1992b; Beltrao and Ben Asher, 1997; Simunek et al., 1998aSimunek et al., 1998b). Clearly there is a need for comprehensive generic models that account for different crops, water and field management practices. The objective of this work is to develop a generic model that is applicable to different crops, soils, irrigation systems and water management strategies.

2. The basic equations of the SALTMED model

The SALTMED model includes the following key processes: evapotranspiration, plant water uptake, water and solute transport under different irrigation systems, drainage and the relationship between crop yield and water use. A brief description of the above-mentioned processes will be given in the following sections.

2.1. Evapotranspiration

The evapotranspiration has been calculated using the Penman–Monteith equation according to the modified version of FAO-56 (1998) in the following form:

$$\mathrm{ET_o} = \frac{0.408\Delta(R_n - G) + \gamma\dfrac{900}{T+273}U_2(e_S - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{1}$$

where $\mathrm{ET_o}$ is the reference evapotranspiration, (mm day^{-1}), R_n is the net radiation, (MJ m^{-2} day^{-1}), G is the soil heat flux density, (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height, (°C), Δ is the slope of the saturated vapour pressure curve (kPa °C^{-1}), γ is the psychrometric constant, 66 Pa °C^{-1}, e_s is the saturated vapour pressure at air temperature (kPa), e_a is the prevailing vapour pressure (kPa), and U_2 is the wind speed at 2 m height (m s^{-1}). The calculated $\mathrm{ET_o}$ here is for short well-watered green grass.

In the absence of meteorological data (temperature, radiation, wind speed, etc.) and if Class A pan evaporation data are available, the SALTMED model can use these data to calculate the $\mathrm{ET_o}$ according to the FAO-56 (1998) procedure. The model can also calculate the net radiation from the solar radiation if the net radiation data are not available. The crop evapotranspiration $\mathrm{ET_c}$ is calculated as:

$$\mathrm{ET_c} = \mathrm{ET_o}(K_{cb} + K_e) \tag{2}$$

where K_{cb} is the crop transpiration coefficient (known also as basal crop coefficient) and K_e is the soil evaporation coefficient. The values of K_{cb} and K_c, for each growth stage and the duration of each growth stage for different crops are available in the model's database. These data can be used in the absence of measured values. K_e is calculated according to FAO-56 (1998). K_{cb} and K_c are adjusted according to FAO-56 (1998) for wind speed and relative humidity different from 2 m s^{-1} and 45%, respectively.

2.2. Effective rainfall

The effective rainfall, i.e. the part of the rainfall that is available for infiltration through the soil surface, is estimated in the model in three ways:

1. as a percentage of total rainfall;
2. calculated according to the FAO-56 (1998) procedure;
3. taken to be equal to total rainfall.

2.3. Plant water uptake in the presence of saline water

2.3.1. The actual water uptake rate

Different approaches have been suggested by a number of authors, for example, Šimůnek and Suarez (1994), Van Genuchten and Hoffman (1984), and Van Genuchten (1987). The formula adopted in the SALTMED model is that suggested by Cardon and Letey (1992a), which determines the water uptake S (d^{-1}) as:

$$S(z,t) = \left[\frac{S_{\max}(t)}{1 + \left(\dfrac{a(t)h + \pi}{\pi_{50}(t)}\right)3}\right]\lambda(z,t) \tag{3}$$

where

$$\lambda(z) = 5/3L \text{ for } z \leq 0.2l \tag{4}$$

$$\lambda(z) = 25/12L*(1 - z/L) \text{ for } 0.2L < z \leq L \tag{4a}$$

$$\lambda(z) = 0.0 \text{ for } z > L \tag{4b}$$

where $S_{\max}(t)$ is the maximum potential root water uptake at the time t; z is the vertical depth taken positive downwards, $\lambda(z,t)$ is the depth- and time-dependent fraction of total root mass, L is the maximum rooting depth, h is the matric pressure head, π is the osmotic pressure head; $\pi_{50}(t)$ is the time-dependent value of the osmotic pressure at which $S_{max}(t)$ is reduced by 50%, and $a(t)$ is a weighing coefficient that accounts for the differential response of a crop to matric and solute pressure. The coefficient $a(t)$ equals $\pi_{50}(t)/h_{50}(t)$ where $h_{50}(t)$ is the matric pressure at which $S_{max}(t)$ is reduced by 50%.

2.3.2. The maximum water uptake $S_{max}(t)$

$S_{max}(t)$is calculated as:

$$S_{max}(t) = ET_o(t)*K_{cb}(t) \quad (5)$$

2.3.3. The rooting depth

The rooting depth was assumed to follow the same course as the crop coefficient K_c. Therefore, it has been described by the following equation:

$$\text{Root depth}(t) = [\text{Root depth}_{min} + (\text{Root depth}_{max} - \text{Root depth}_{min})]*K_c(t)/K_{cmax} \quad (6)$$

The maximum root depth is available either from direct measurements or from the literature.

2.3.4. The rooting width

Compared with rooting depth, there is a very little information in the present literature on lateral extent of the rooting systems of field crops over time. Therefore, a simple equation has been suggested as follows:

$$\text{Root width}(t) = [\text{Root width}/\text{Root depth}]\text{ratio}*\text{Root depth}(t) \quad (7)$$

The [Root width/Root depth] ratio is dependant on the crop and soil type and other factors. It can be obtained either from experimental data or from the literature. The values of h_{50} and π_{50} can be obtained from experiments or from literature such as FAO-48 (1992).

2.4. Relative and actual crop yield

2.4.1. The relative crop yield, RY

Due to the unique and strong relationship between water uptake and biomass production, and hence the final yield, the relative crop yield RY is estimated as the sum of the actual water uptake over the season divided by the sum of the maximum water uptake (under no stress condition) as:

$$RY = \frac{\sum S(x,z,t)}{\sum S_{max}(x,z,t)} \quad (8)$$

2.4.2. The actual yield, AY

The actual yield, AY is simply obtainable by:

$$AY = RY*Y_{max} \quad (9)$$

where Y_{max} is the maximum yield obtainable in a given region under optimum and stress-free condition.

2.5. Water and solute flow

The water flow in soils can be described mathematically by the well-known Richard's equation. It is a partial non-linear differential equation, partial in time and space. It is based on two soil physical principles: Darcy's law and mass continuity. Darcy's law reads:

$$q = -K(h)\frac{\delta H}{\delta Z} \quad (10)$$

where q is the water flux, $K(h)$ is the hydraulic conductivity as a function of soil water pressure head, Z is the vertical coordinate directed downwards with its origin at soil surface, and H is the hydraulic head which is the sum of the gravity head, Z, and the pressure head, ψ, thus:

$$H = \psi + Z \quad (11)$$

The vertical transient-state flow water in a stable and uniform segment of the root zone can be described by a Richard's type equation as:

$$\frac{\partial\theta}{\partial t} = -\frac{\partial}{\partial z}\left[K(\theta)\frac{\partial(\psi + z)}{\partial z}\right] - S_w \quad (12)$$

where θ is volume wetness; t is the time; z is the depth; $K(\theta)$ is the hydraulic conductivity (a function of wetness); ψ is the matrix suction head; and S_w is the sink term representing extraction by plant roots. The movement of solute in the soil system, its rate and direction, depends greatly on the path of water movement, but it is also determined by diffusion and hydrodynamic dispersion. By the combination of the diffusion, the dispersion and the convection the overall flux of solute J can be obtained according to Hillel (1977) as:

$$J = -(D_h + D_s)(\partial c/\partial x) + \bar{v}\theta c \quad (13)$$

where c is the concentration of solute in the flowing water and $\bar{v}$ is the average velocity of the flow, D_s is the solute diffusion in soil which decreases due to the fact that the liquid phase occupies only a fraction of soil volume, and also due to the tortuous nature of the path. It can, therefore, be expressed according to the following equation where D_0 is the diffusion coefficient

$$D_s = D_0\theta\xi \quad (14)$$

where

$$\xi = \theta^{7/3}/\theta_s^2 \quad (15)$$

where ξ is the tortuosity, an empirical factor smaller than unity, which can be expected to decrease with decreasing θ (Šimůnek and Suarez, 1994). The convection flux generally causes hydrodynamic dispersion too, an effect that depends on the microscopic non-uniformity of flow velocity in the various pores. Thus a sharp boundary between two miscible solutions becomes increasingly diffuse about the mean position of the front. For such a case, the diffusion coefficient has been found by Bresler (1975) to depend linearly on the average flow velocity $\bar{v}$, as follows:

$$D_h = \alpha\bar{v} \tag{16}$$

where α is an empirical coefficient.

If one takes the continuity equation into consideration, one-dimensional transient movement of a non-interacting solute in soil can be expressed as:

$$\frac{\partial(\theta c)}{\partial t} = \frac{\partial}{\partial z}\left(D_a\frac{\partial c}{\partial z}\right) - \frac{\partial(qc)}{\partial z} - S_s \tag{17}$$

where c is the concentration of the solute in the soil solution, q is the convective flux of the solution, D_a is a combined diffusion and dispersion coefficient, and S_s is a sink term for the solute representing root adsorption/uptake.

Under irrigation from a trickle line source, the water and solute transport can be viewed as two-dimensional flow and can be simulated by one of the following:

1. a 'plane flow' model involving the Cartesian coordinates x and z. Plane flow takes place if one considers a set of trickle sources at equal distance and close enough to each other so that their wetting fronts overlap after a short time from the start of the irrigation.
2. a 'cylindrical flow' model described by the cylindrical coordinates r and z.

Cylindrical flow takes place if one considers the case of a single trickle nozzle or a number of nozzles spaced far enough apart so that overlap of the wetting fronts of the adjacent sources does not take place. For a stable, isotropic and homogeneous porous medium, the two-dimensional flow of water in the soil can be described according to Bresler (1975) as:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\theta)\frac{\partial\psi}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial(\psi + z)}{\partial z}\right] \tag{18}$$

where x is the horizontal coordinate; z is the vertical-ordinate (considered to be positive downward); $K(\theta)$ is the hydraulic conductivity of the soil. Considering isotropic and homogeneous porous media with principal axes of dispersion oriented parallel and perpendicular to the mean direction of flow, the hydrodynamic dispersion coefficient D_{ij} can be defined as follows:

$$D_{ij} = \lambda_T|V|\delta_{ij} + (\lambda_L - \lambda_T)V_iV_j/|V| + D_s(\theta) \tag{19}$$

where λ_L is the longitudinal dispersivity of the medium; λ_T is the transversal dispersivity of the medium; δ_{ij} is Kronecker delta (i.e. $\delta_{ij} = 1$ if $i = j$ and $\delta_{ij} = 0$ if $i \neq j$); V_i and V_j are the ith and jth components of the average interstitial flow velocity V, respectively, $V = (V_x^2 + V_z^2)^{1/2}$ and $D_s(\theta)$ is the soil diffusion coefficient as defined in Eq. (14). If one considers only two dimensions and substituting D_{ij}, the salt flow equation becomes:

$$\frac{\partial(C\theta)}{\partial t} = \frac{\partial}{\partial x}\left(D_{xx}\frac{\partial C}{\partial x} + D_{xz}\frac{\partial C}{\partial z} - q_xC\right) + \frac{\partial}{\partial z}\left(D_{zz}\frac{\partial C}{\partial z} + D_{zx}\frac{\partial C}{\partial x} - q_zC\right) \tag{20}$$

In the model, sprinkler, flood and basin irrigation are described by one-dimensional flow equations (e.g. Eqs. (12) and (17)). Furrow and trickle line source are described by two-dimensional equations (e.g. Eqs. (18) and (20)). Trickle point source is described by cylindrical flow equations obtained by replacing x by the radius r and rearranging Eqs. (18) and (20) as given by Bresler (1975) and Fletcher Armstrong and Wilson (1983). The water and solute flow equations were solved numerically using a finite difference explicit scheme. The boundary conditions are those given by Ragab et al. (1984), Bresler (1975) and Brandt et al. (1971). As a result, the model is able to produce time series distributed values of:

1. The soil moisture content, θ;
2. The salt concentration, C;
3. The total salt content, $C*\theta$;
4. The relative concentration as:

$$\{C(z,t) - C_{\text{irrigation water}}\}/C_{\text{initial}}(z,t) \tag{21}$$

2.5.1. Soil hydraulic parameters

Solving the water and solute transport equations require two soil water relations namely the soil moisture–water potential relation and the soil water potential–hydraulic conductivity relation. They were taken according to Van Genuchten (1980) as:

$$\theta(h) = \theta_r + [(\theta_s - \theta_r)/(1 + |\alpha h|^n)^m] \tag{22}$$

$$K(h) = K_sK_r(h) = K_sSe^{1/2}[1-(1-Se^{1/m})^m]^2 \tag{23}$$

where θ_r and θ_s denote the residual and the saturated moisture contents, respectively; K_s and K_r are the saturated and relative hydraulic conductivities respectively, α and n are the shape parameters, $m = 1-1/n$ and S_e is effective saturation or normalised volumetric soil water content. α and n are empirical parameters.

Eqs. (22) and (23) were used after being re-arranged to obtain the soil water potential and hydraulic conductivity as functions of effective saturation according to van Dam et al. (1994) as:

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) \tag{24}$$

$$h(S_e) = [(S_e^{-1/m} - 1)^{1/n}]/\alpha \tag{25}$$

$$K(S_e) = K_sSe^{1/2}[1-(1-S_e^{1/m})^m]^2 \tag{26}$$

Based on Pedotransfer functions, Rawls and Brakensiek (1989), produced values of θ_r, θ_s, θ, K_s, water content at field capacity and wilting point, bubbling pressure and n and m (as $n = \lambda + 1$ and $m = \lambda/n$) for several soil types where λ is the pore size distribution index. These values and other values obtained from different sources are included in the model's database and can be used as default values in the absence of measurements. The model could also use tabulated pair values of both soil moisture–soil water potential and soil moisture–-hydraulic conductivity and interpolate for in-between range values.

2.6. Drainage

Free drainage at the bottom of the root zone is assumed otherwise an impermeable layer is assumed at the bottom of the soil profile.

2.7. Leaching requirements

The experimental results showed that the soil salinity does not reduce crop yield significantly until a threshold level is exceeded. To avoid yield loss when salt concentrations exceed their tolerance limits, excess salts must be leached below the root zone. Thus, when the net depth of applied water is calculated for scheduling, an additional depth of water based on the salinity level should be added for leaching. The leaching requirement (LR) is usually calculated as:

$$\mathrm{LR} = \frac{D_d}{D_i} = \frac{C_i}{C_d} \tag{27}$$

where D_d is the depth of water passing below the root zone as drainage water, D_i is the depth of applied irrigation+rainfall water, C_d is the salt concentration of the drainage water above which yield reduction occurs and C_i is the salt concentration of the irrigation water.

The LR is simply calculated in the SALTMED model as a ratio of the salt concentration of the irrigation water to that of the drainage water or the mean salinity level of the root zone as given in Eq. (27). The relative salt concentration as given in Eq. (21) could be used as an indicator for the need to leach the accumulated salts in the root zone.

2.8. Data requirements

1. *Plant characteristics* for each growth stage include the crop coefficient, K_c, K_{cb}, root depth and lateral expansion, crop height and maximum/potential final yield observed in the region under optimum conditions.
2. *Soil characteristics* include depth of each soil horizon, saturated hydraulic conductivity, saturated soil moisture content, salt diffusion coefficient, longitudinal and transversal dispersion coefficient, initial soil moisture and salinity profiles, and tabulated data of soil moisture versus soil water potential and soil moisture versus hydraulic conductivity.
3. *Meteorological data* include daily values of temperature (maximum), temperature (minimum), relative humidity, net radiation, wind speed, and daily rainfall.
4. *Water management data* include the date and amount of irrigation water applied and the salinity level of each applied irrigation.
5. *Model parameters:*

- Include the number of compartments in both vertical and horizontal direction.
- The maximum time step for calculation.

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2.9. Default data in the databases

The model has three built-in databases:

1. *Crop database* (based largely on the FAO papers 48, 1992, FAO-56, 1998), contains different crops, trees and shrubs (>200) from different regions, duration of each growth stage, sowing and harvest dates, K_c and K_{cb} values for each growth stage maximum height and maximum rooting depth.
2. *Soils database* contains the hydraulic characteristics and solute transport parameters of more than 40 different soil types.
3. *Irrigation system database* contains information on

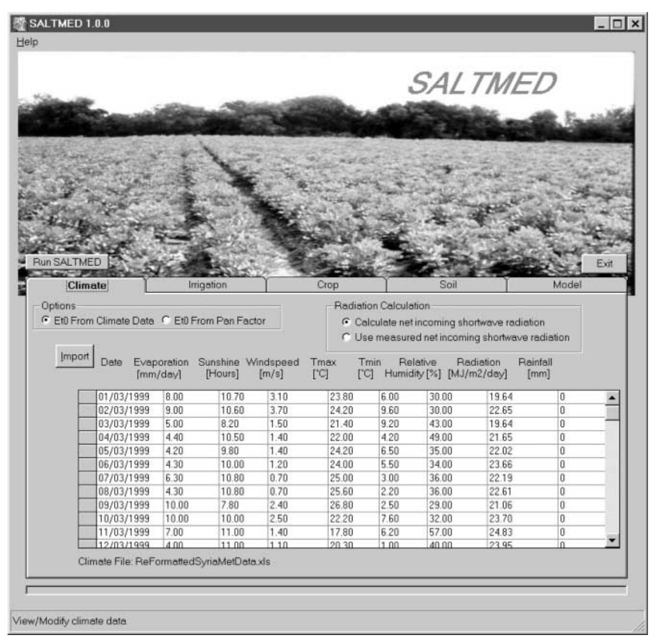

Fig. 1. The meteorological data input file (for all examples).

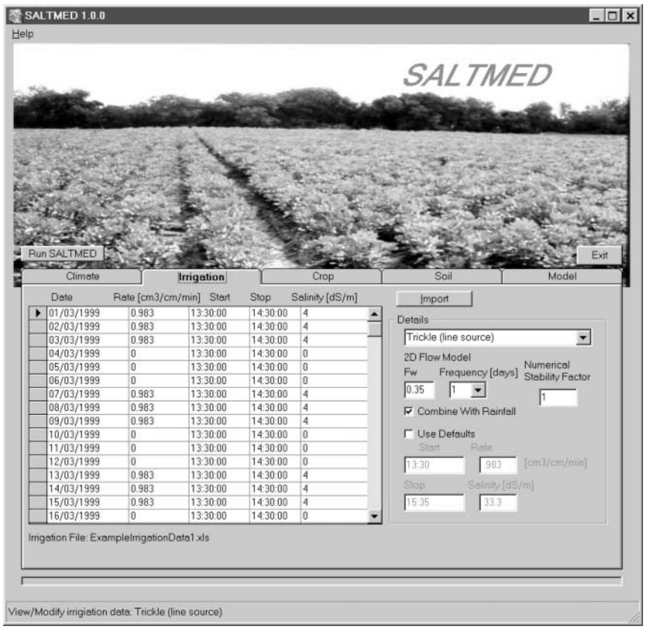

Fig. 2. The irrigation data input file (Example 1).

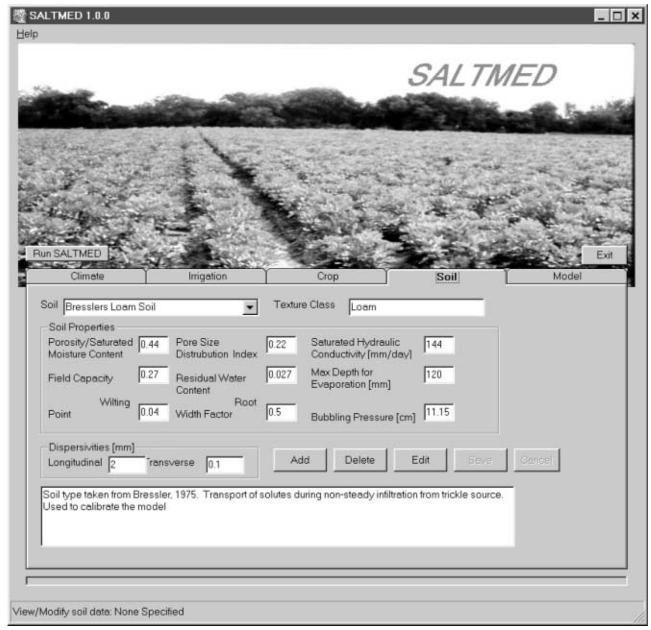

Fig. 4. The soil parameters input menu (Example 1).

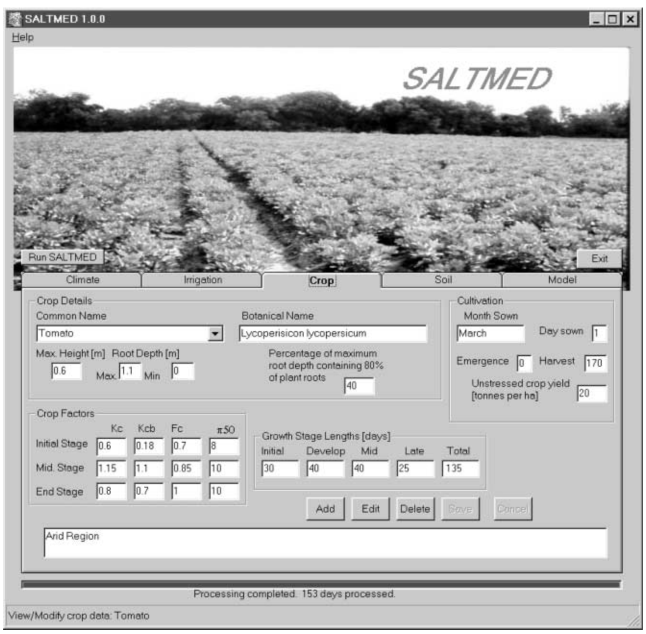

Fig. 3. The crop parameters input menu (for all examples).

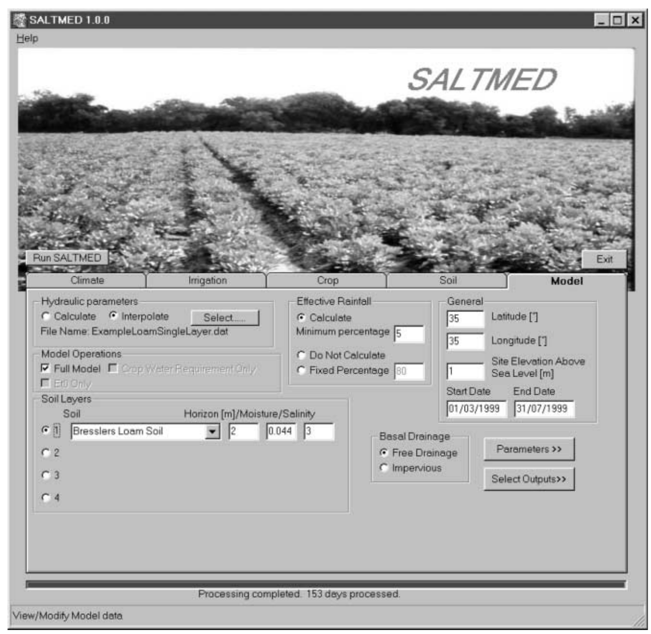

Fig. 5. The soil input data file, run , drainage and effective rainfall options.

the wetting fraction and the frequency of application of ten irrigation systems.

3. Model results and discussion

The code of this model was written in C/C^{++} for Windows 95/98 operation system. The model output is given as text and graphical files. These include horizontal and vertical distribution of soil moisture, soil salinity, relative concentration, soil matric potential profiles and time series of reference, crop transpiration, bare soil evaporation, leaching requirements, irrigation amounts, K_c, K_{cb}, root depth and final yield.

There was difficulty in finding data sets suitable for model testing for a full growing season where the different processes were acting simultaneously. Therefore, full testing of the model is awaiting the ongoing data collection from two sites in Syria and Egypt, specifically conducted to test the model. However, during model development, different subroutines were tested separately. For

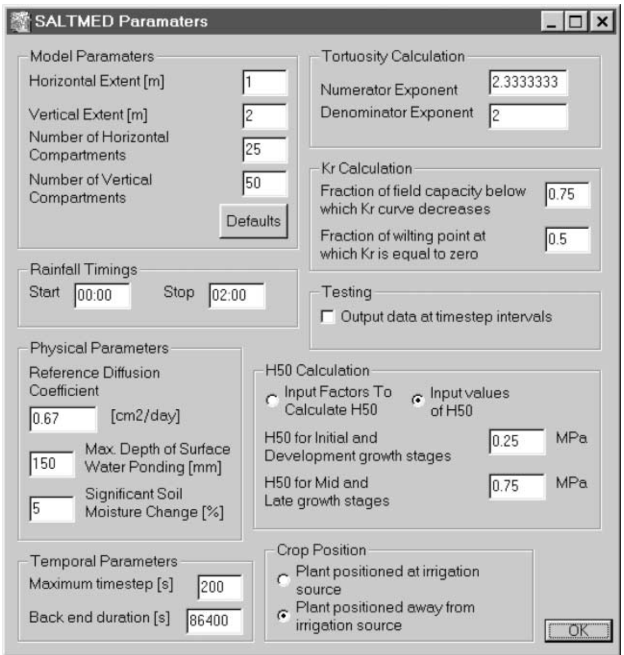

Fig. 6. Model parameters menu.

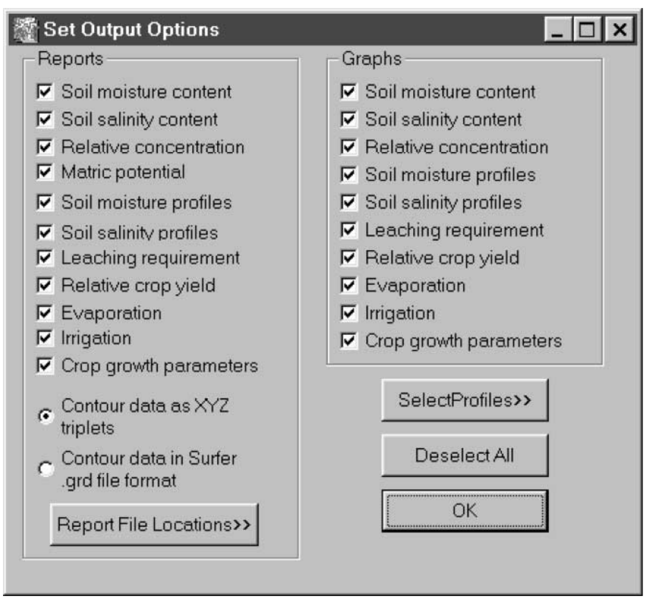

Fig. 7. The output option menu.

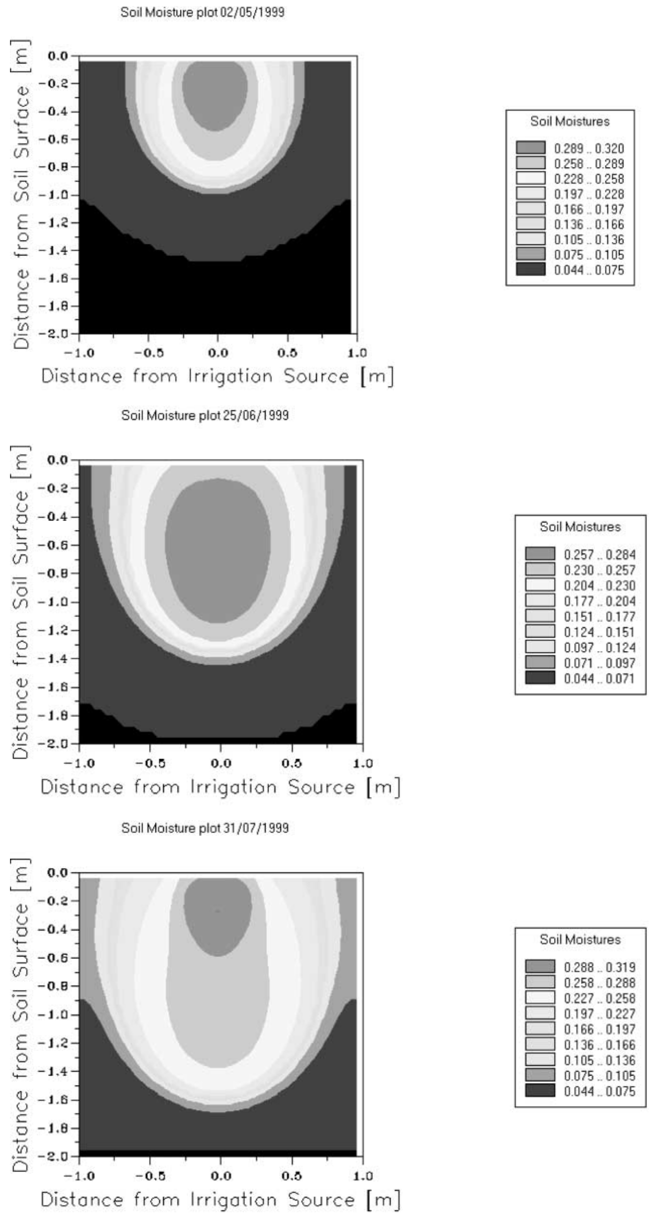

Fig. 8. Evolution of soil moisture profile over time under trickle line source (Example 1).

example, when run only as an infiltration model, the model was able to reproduce the soil moisture, salinity and relative concentration profiles of Gilat Loam under trickle line source with a discharge rate of 0.983 cm^3 cm^{-1} min^{-1} according to Bresler (1975); soil moisture profiles of sand under trickle line source according to Ragab et al. (1984); and soil moisture profile of stratified soil (three layers) of Lakeland Sand under trickle point source according to Fletcher Armstrong and Wilson (1983). These small tests were for the short duration infiltration process without any account of water uptake or evaporation. In this paper the model's performance over the whole growing season of a tomato crop has been assessed. Five different examples were carried out as follows:

Example 1: *Meteorological data:* data from Dair-Ezore Syria, from March 1,1999 until July 31, 1999 (Fig. 1). *Irrigation:* trickle irrigation line source with discharge rate of 0.983 cm^3 cm^{-1} min^{-1} (Bresler, 1975) and salinity of 4 dS m^{-1} (Fig. 2). *Crop:* tomato, FAO-56 (1998) (Fig. 3). *Soil:* Bresler Loam soil (Bresler, 1975) for 2 m deep with initial salinity equal to 3 dS m^{-1} (Figs. 4 and 5). *Model parameters:* the

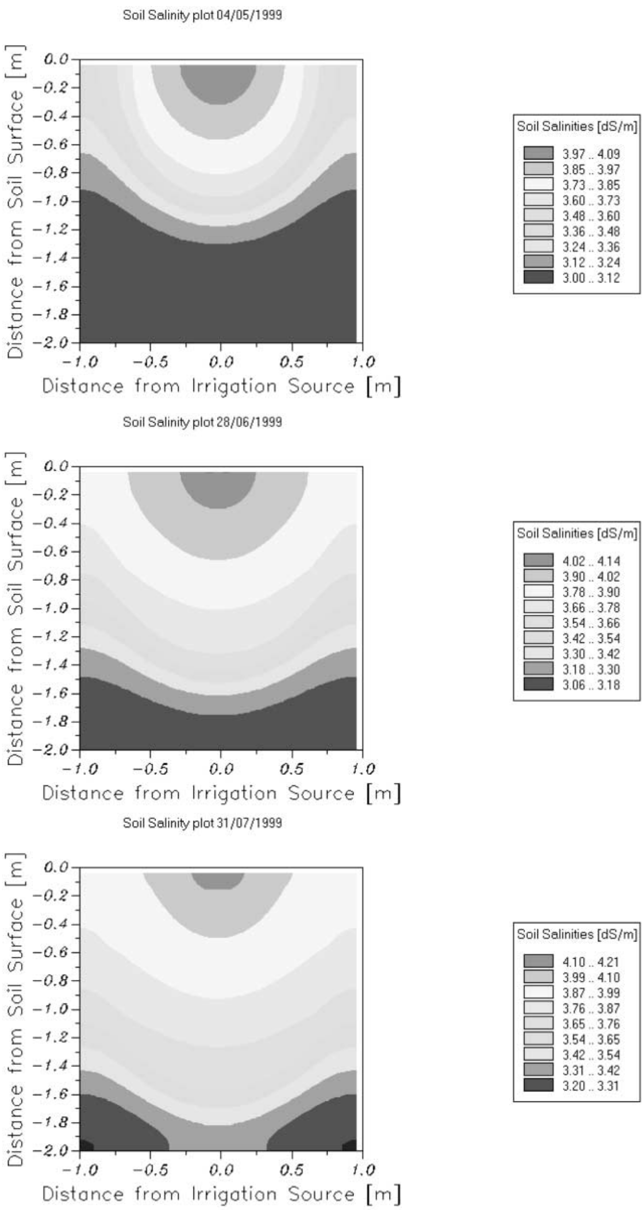

Fig. 9. Evolution of soil salinity profile over time under trickle line source (Example 1).

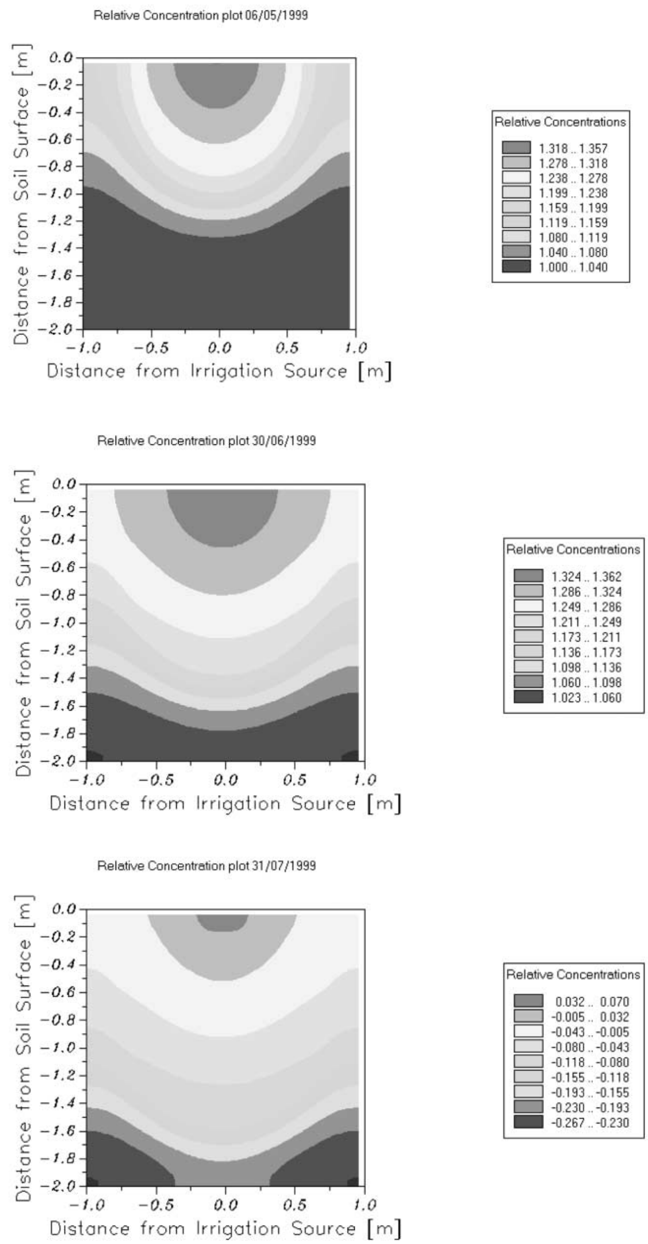

Fig. 10. Evolution of relative salinity profile over time under trickle line source (Example 1).

calculations were performed on 4 cm × 4 cm grid squares with maximum time step 200 s (Fig. 6).

Example 2: as in Example 1 but applying low saline irrigation water 0.4 dS m^{-1}.

Example 3: as in Example 1 but applying 4 l h^{-1} using basin irrigation.

Example 4: as in Example 1 but applying 4 l h^{-1} using trickle point source (Fletcher Armstrong and Wilson, 1983).

Example 5: as in Example 1 but with three layers Lakeland Sandy Soil (Fletcher Armstrong and Wilson, 1983).

The model produces a number of daily output results which can be selected according to Fig. 7 either as data files or figures or both. The model was successfully run with data of Example 1. The soil moisture, salinity and relative salinity profiles for only three days May 2, June 25 and July 31, 1999 were selected and shown in Figs. 8–10 respectively. The vertical and horizontal distribution of soil moisture and salinity for July 31 (last day of the run) is shown in Fig. 11. These figures show the evolution of soil moisture and the change of the wet bulb size over the five months period. One can notice that there is a slight increase in soil salinity from the initial value of 3 dS m^{-1} on March 1 to 4 dS m^{-1} on July 31. This value of 4 dS m^{-1} is close to the value of the irri-

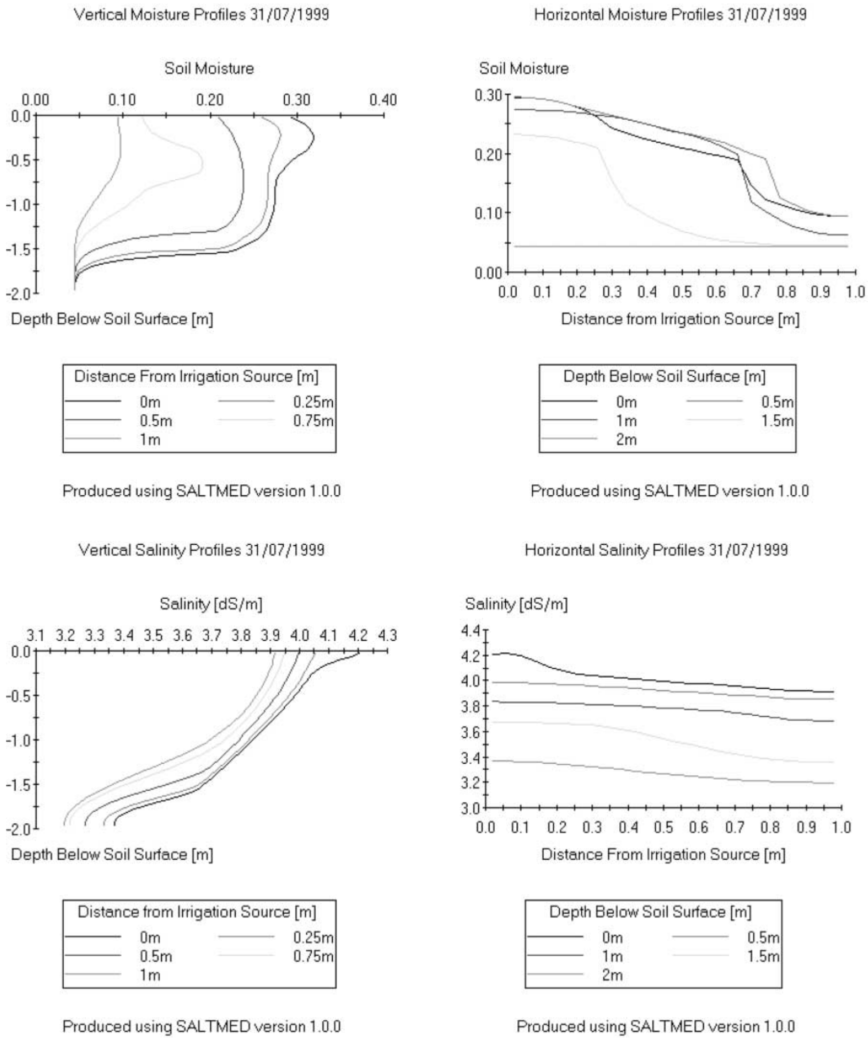

Fig. 11. Vertical and horizontal distribution of moisture and salinity under trickle line source (Example 1).

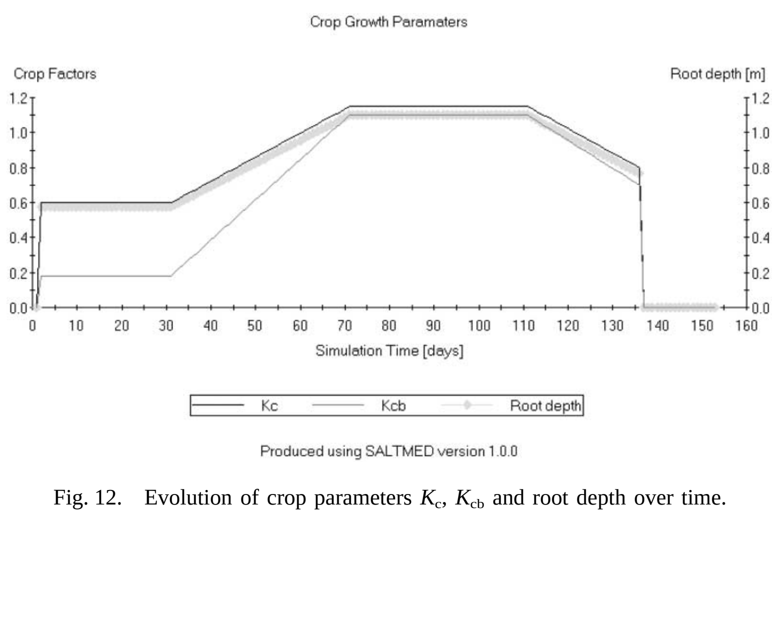

Fig. 12. Evolution of crop parameters K_c, K_{cb} and root depth over time.

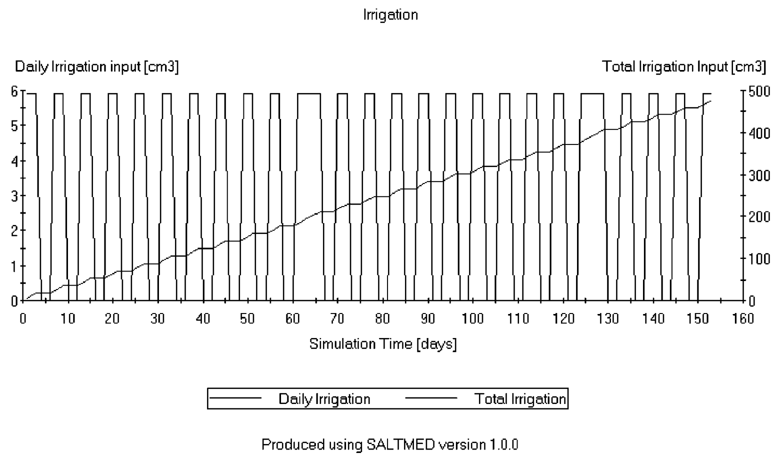

Fig. 13. Irrigation time, amount and cumulative irrigation amount (Example 1).

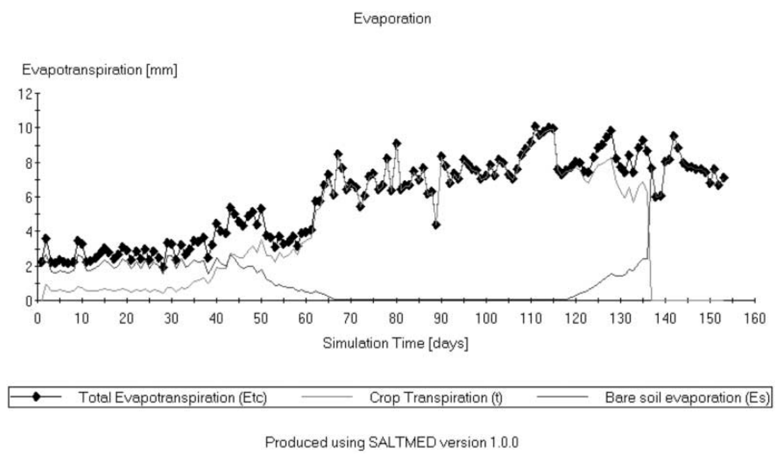

Fig. 14. Total crop evapotranspiration, transpiration and bare soil evaporation (Example 1).

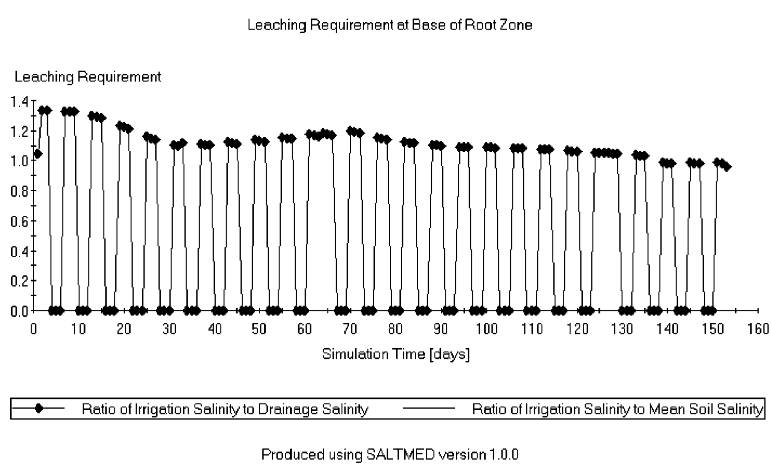

Fig. 15. The leaching requirement over time (Example 1).

gation water salinity and it is mainly associated with the top layers as shown in Fig. 11.

The evolution of crop parameters K_c, K_{cb} and root depth with time for the tomato are shown in Fig. 12 while the daily irrigation amount as well as the total seasonal amount are shown in Fig. 13. The crop evapotranspiration Et_c and its components crop transpiration and bare soil evaporation are shown in Fig. 14,. This figure

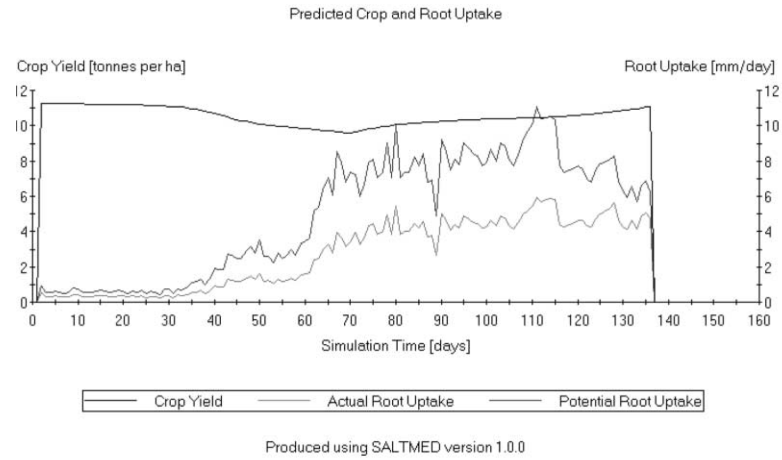

Fig. 16. Crop potential and actual water uptake and yield (Example 1).

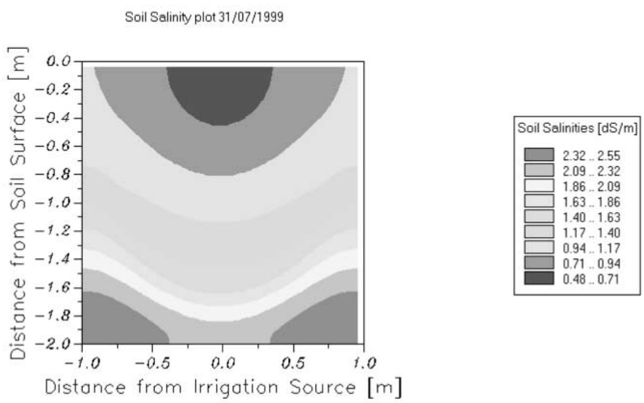

Fig. 17. Soil salinity profile under trickle line source (0.4 dS m−1) (Example 2).

illustrates clearly that at the beginning of the growing season bare soil evaporation is more dominant than crop transpiration but becomes negligible when the crop reaches its maximum canopy cover at which the K_{cb} reaches its maximum value and the crop transpiration becomes more dominant until the beginning of the late stage of the growth. This is followed by a decline in crop transpiration and rise in bare soil evaporation until the harvest day where the transpiration becomes zero and bare soil evaporation becomes the main component of the Et_c.

By July 31, the leaching requirements, as shown in Fig. 15 indicate that the value is closer to 1. This means that the salinity of the irrigation water is nearly equal to the mean salinity level of the root zone or drainage water. Therefore, applying flood irrigation before the next crop with fresh water to leach the accumulated salts in the root zone might be desirable especially if the next crop has a threshold value closer to 4 dS m^{-1}.

The maximum water uptake (under no stress) and the actual water uptake as well as the expected crop yield, are shown in Fig. 16. The occasional wide gap between the maximum and actual water uptake reflects the effect of salinity stress on the uptake, hence the yield. Under the soil, irrigation water, climatic and field conditions of Example 1 the expected yield is nearly 12 tonnes ha^{-1}.

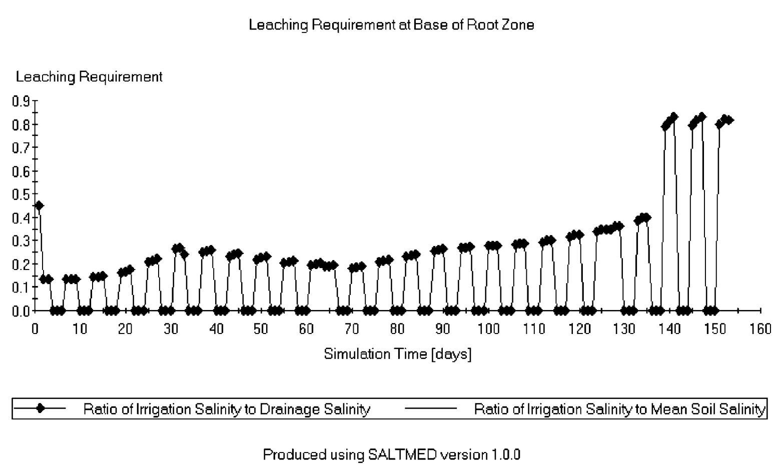

Fig. 18. The leaching requirements under trickle line source (0.4 dS m−1) (Example 2).

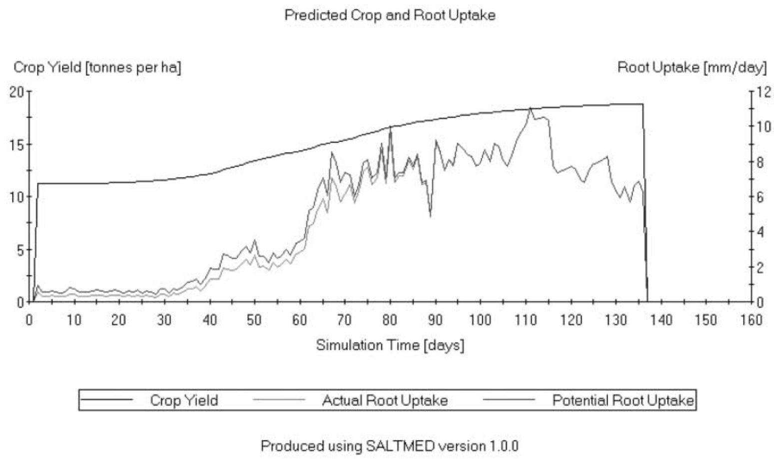

Fig. 19. Crop water uptake and yield under trickle line source (0.4 dS m−1) (Example 2).

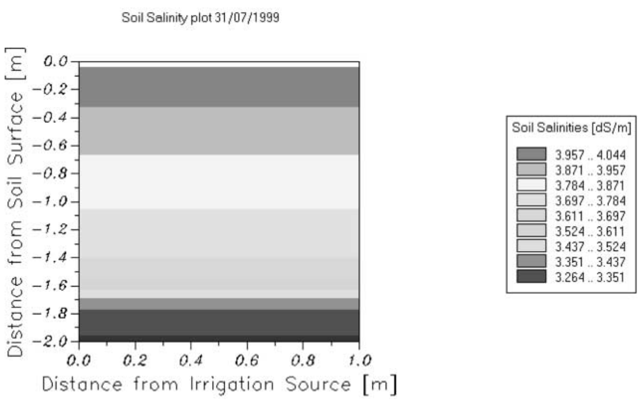

Fig. 20. Salinity profile under basin irrigation (Example 3).

This amounts to 60% (approximately) of the maximum obtainable yield in the region under optimum and stress-free condition. The reduction in crop yield due to the use of saline water is reported widely in the literature and the output of the model is in line with the literature (e.g. Beltrao and Ben Asher, 1997; Rhodes et al., 1992; FAO, 1992, 1998; Hoffman et al., 1990). However, the reduction level depends very much on different factors such as the crop tolerance level, soil salinity, initial conditions, climatic conditions, water management strategy, etc. Our field results based on experiments in Egypt and Syria are under investigation and the preliminary results show that there is a reduction in the yield and that reduction level differed between the two countries even when using the same salinity level for irrigation water due to the impact of other factors (mentioned above). These results are being analysed and soon will be published.

When applying the same conditions of Example 1, i.e. using the same soil, climatic and irrigation input files but using irrigation water with low salinity level as 0.4 dS m^{-1} (Example 2) one can see the effect of reducing the salinity of irrigation water on soil salinity, leaching requirement, and yield. The results shown in Fig. 17 indicate that the soil salinity level has dropped below the initial soil salinity value of 3 dS m^{-1}. Subsequently, the leaching requirement as given in Fig. 18 indicates

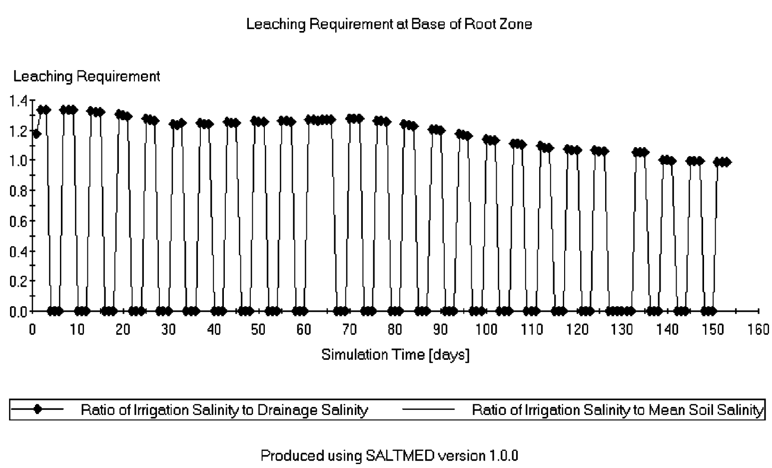

Fig. 21. Leaching requirements under basin irrigation (Example 3).

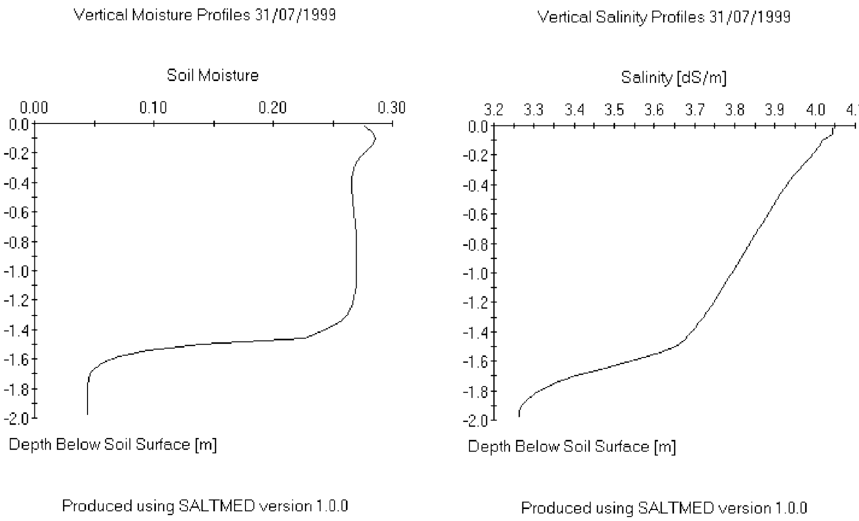

Fig. 22. Soil moisture and salinity distribution under basin irrigation (Example 3).

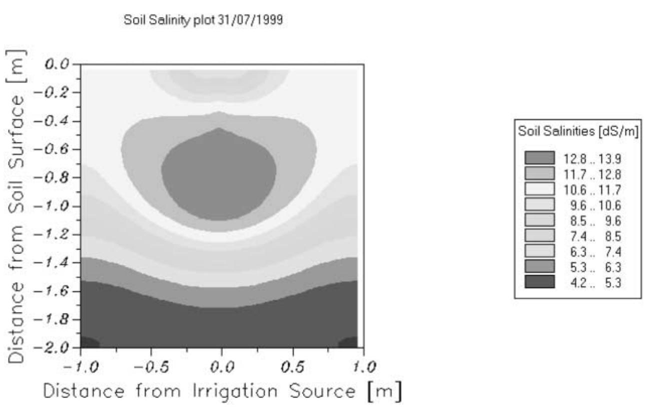

Fig. 23. Soil salinity profile under trickle point source (Example 4).

that in contrast to Example 1 (irrigation water salinity was equal to 4 dS m^{-1}) there is no need for additional leaching before the next crop as the salinity of the irrigation water is below that of the soil. This is an example to illustrate that using irrigation water with low salinity level has resulted in continuous leaching of salts from the soil and reduced the salinity stress effect on actual water uptake. The latter became closer to the maximum water uptake and as a result the expected yield was very close the maximum yield of 20 tonnes ha^{-1} as shown in Fig. 19.

The model's performance has also been assessed using different irrigation systems. Example 3 is for a basin irrigation system with the same soil, crop and climate input data of Example 1. The irrigation water was applied at an assumed rate of 4 l h^{-1}. One can see from Figs. 20 and 22 that there is slight accumulation of salts especially in the top layers. The latter became closer to the salinity of the irrigation water. The leaching requirements as shown in Fig. 21 indicate the salinity of irrigation water and drainage water are very close. Therefore applying irrigation with fresh water before the next crop to leach the accumulated salts in the root zone

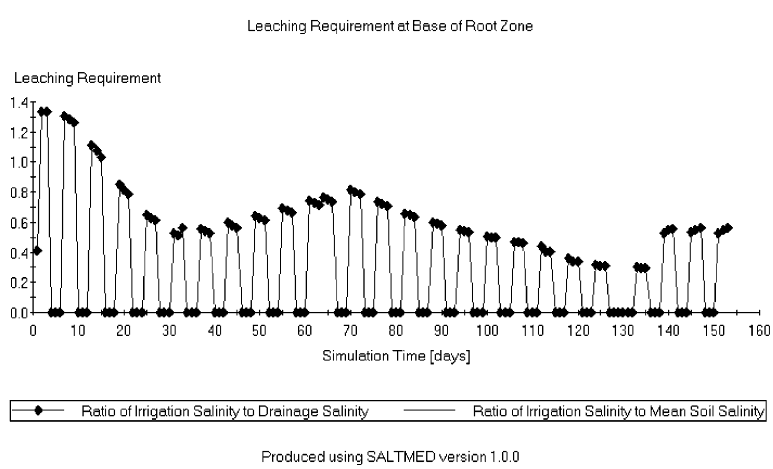

Fig. 24. The leaching requirements under trickle point source (Example 4).

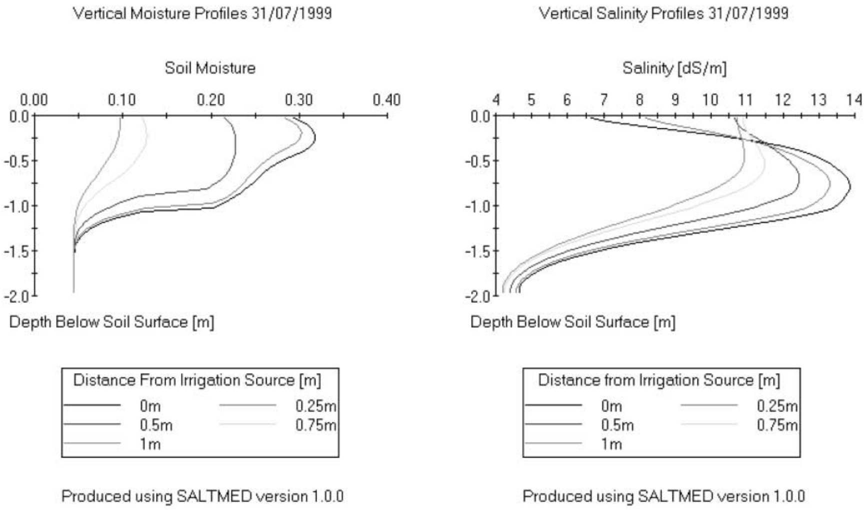

Fig. 25. Soil moisture and salinity distribution under trickle point source (Example 4).

might be desirable especially if the next crop has a lower threshold value less than that of the tomato.

Example 4 used the same input data of soil, crop and climate of Example 1 but using a trickle point source to irrigate at a rate of 4 l h^{-1}. Figs. 23 and 25 show the salinity distribution under the point source. The figure shows accumulation of salts in the subsurface layers (root zone). As the salinity of the soil water becomes greater than salinity of the irrigation water especially the subsurface layers, the leaching requirements go below 1 and approach 0.6 (Fig. 24) by the end of the growing season. In such case a big leaching (flood) will be required before the next crop and possibly during the growing season. Leaching requirements could be applied during the season if the soil salinity level exceeds the critical threshold value of the crop such as the tomato used in this example where its threshold value is 10 dS m^{-1}.

To assess the model's performance on sandy soils, as compared to the loam soil used in the Examples 1–3, an attempt has been made to apply the model on three layers of Lakeland Sand (Fletcher Armstrong and Wilson, 1983) in Example 5. In this example, the data of Example 1 on irrigation amounts, trickle line source system, crop, and climate data were used (Fig. 26). The only difference was the substitution of the loam soil with the three layers of Lakeland Sand. The results showed that the expected high infiltration rate of sandy soils allowed fast movement of water and salts to the bottom of the 2 m soil profile (Fig. 29). Subsequently, there has been an accumulation of salts at the bottom of the 2 m profile while the top layers (root zone) had a salinity level closer to the one of the irrigation water (4 dS m^{-1}). This was also reflected in the leaching requirement (Fig. 27) where by the end of the season the irrigation water salinity was closer to the root zone salinity and the leaching requirement was closer to 1. A small leaching might

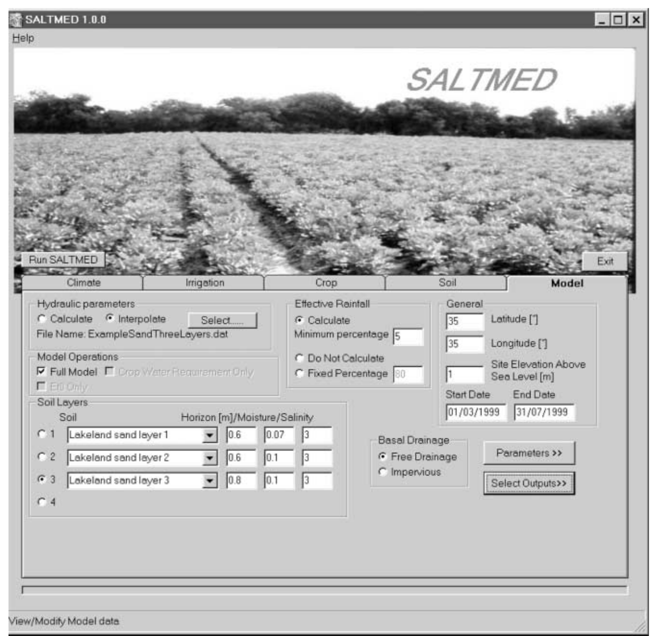

Fig. 26. Soils input data file for Example 5 (trickle line source).

be desirable before the next crop especially if the next crop has a lower threshold value than the tomato. When compared with the loamy soil of Example 1 the sandy soil (Fig. 28) produced a yield of 15 tonnes ha^{-1}, approximately 75% of the maximum yield compared with 60% under loam soil, this is largely due to the fast leaching of salt below the root zone in the sandy soils.

4. Conclusions

Generally the use of saline water for irrigation requires a selection of appropriate salt tolerant crops and an improvement in water management and maintenance

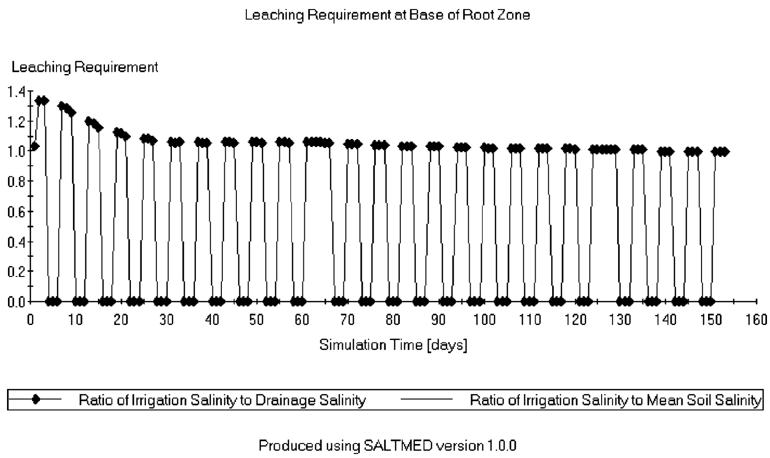

Fig. 27. The leaching requirements for the Lakeland Sand (Example 5).

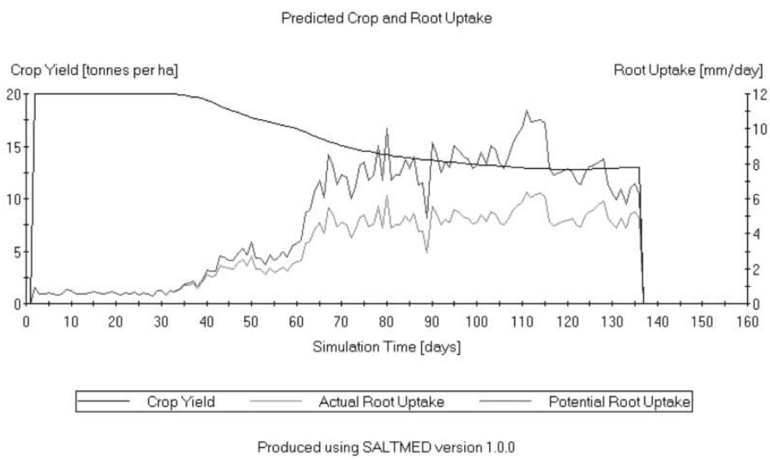

Fig. 28. Crop water uptake and yield of the Lakeland Sand (Example 5).

of soil physical properties to ensure adequate soil permeability to meet leaching requirements. As such an integrated approach is the way forward to facilitate the use of saline waters for irrigation, to minimise drainage disposal problems and to maximise the beneficial use of multiple water sources. Soil salinisation is a long-term process, long duration experiments, as well as robust comprehensive, rather than single-process orientated models are required for long-term predictions. The SALTMED model has been developed to meet these challenges. In this paper the principles and the integrated management approach of the SALTMED model have been highlighted. The model has the potential to be applied under a variety of irrigation systems, soil types, soil stratifications, crops, water qualities and water application strategies (e.g. Blending, Cyclic). The model has been run with five examples of application using data from the literature. The model was able to illustrate the effect of the irrigation system, the soil type, the irrigation salinity level on soil moisture and salinity distribution, leaching requirements, and crop yield. The model performance in all cases was, as one would expect under the given conditions. The model is friendly and easy to use benefiting from the Windows™ environment, however, it is a physically based model using the well-known water and solute transport, evapotranspiration, and water uptake equations. A follow up paper will show the results of the model tests using data from the experimental sites in Egypt and Syria.

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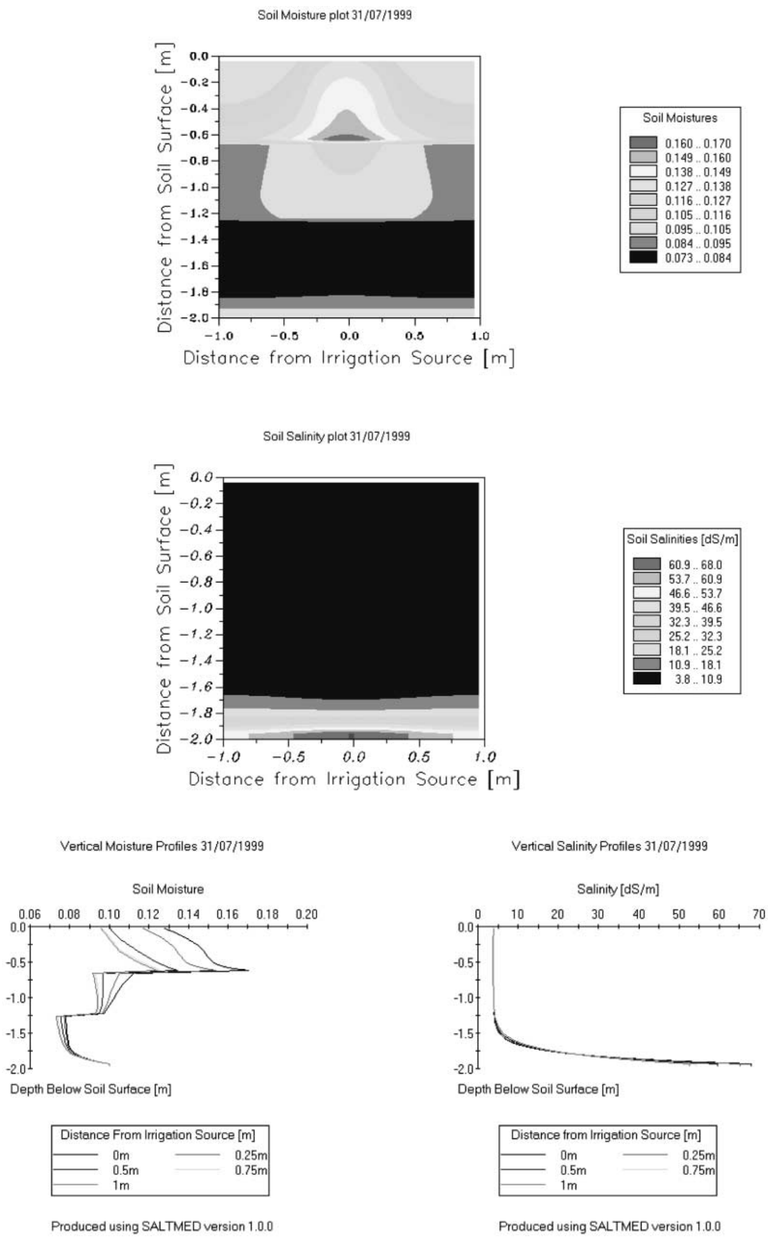

Fig. 29. Soil moisture and salinity distribution of the Lakeland Sand (Example 5).

from Syria who died in accident while on fieldwork in Yemen.

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