SALTMED MODEL AS AN INTEGRATED MANAGEMENT TOOL FOR PRECISION MANAGEMENT OF WATER, CROP, SOIL AND FERTILIZERS

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ABSTRACT

Models can be very useful tools in agriculture water management. Not only could they help in irrigation scheduling and crop water requirement estimation but, they could also be used to predict yield and soil salinization. There are models which are designed for a specific irrigation system or for a specific process e.g. water and solute movement, infiltration, leaching or water uptake by plant roots. The SALTMED model has been developed as a generic model that can be used for a variety of irrigation systems, soil types, soil stratifications, crops and trees, water application strategies (e.g.blending, cyclic) and different water qualities (e.g. fresh, saline). The early version of the model (Ragab, 2002) was successfully tested against field data from Egypt and Syria (Ragab et al., 2005). Since then, the model has been undergoing several developments. The current version, SALTMED 2009, includes the following sub-models: soil temperature, dry matter, soil nitrogen dynamics, subsurface irrigation, deficit irrigation including the Partial Root Drying (PRD), evapotranspiration using Penman-Monteith equation with different options to obtain the canopy conductance from Absecic acid (ABA) concentration and leaf water potential, from environmental parameters, from direct measurements or from estimated values and a utility to save input files and parameters as text file for multiple runs. SALTMED 2009 has been tested successfully against field experimental data from Italy, Serbia and Crete. This paper will describe the SALTMED 2009 model and its components while a follow up paper will show the results of the application.

Keywords: SALTMED model, Irrigation, Salinity, Modelling, Soil moisture, Yield, Dry Matter, Nitrogen, Agricultural Water Management.

INTRODUCTION

Agricultural water use has increased 5 fold since 1940 and now accounts for almost 70 to 80% of world fresh water use.

In some parts of the world, the huge water demand resulted in significant over-exploitation of fresh water resources. In coastal regions, over-exploitation of groundwater can cause the groundwater level to fall below the seawater level and, in presence of permeable stratum, seawater can flow into the aquifer and turn the water brackish. Once contaminated, the aquifer salinity will persist until diluted by rainfall; which may not take place as long as exploitation exceeds recharge.

In many areas, agriculture had to resort to the use of alternative, non-conventional water resources for irrigation; e.g. re-use of agriculture drainage water, use of brackish water, seawater, desalinated saline water, treated waste water, etc. Irrigation with non-conventional water resources, however, means care should be exercised not to harm the environment or cause soil degradation, Ragab (1997, 1998, 2002, 2004), Hamdy et al. (2003) and Malash et al. (2008).

Studies and field practices have shown that, under a proper management system, crops of moderate to high salt tolerance can be irrigated with saline water, especially at later growth stages. High salt concentrations limit plant growth by making water less available for uptake by the roots. As salt movement is intimately tied to water movement, salinity management in any irrigation system is largely a function of water management.

A truly integrated approach is essential as management of soil or crop or water in isolation would lead to soil deterioration; increase in water table levels, causing further soil salinisation; reduction in oxygen levels in the root zone, which would affect nutrients availability; and possibly create wet lands, which could be a health hazard, e.g. increase the risk of malaria.

SALTMED model has been developed for such generic applications (Ragab, 2002, 2005, 2009). Dry matter production, yield, soil salinity, soil moisture profiles, salinity leaching requirements, soil nitrogen dynamics, nitrate leaching, soil temperature, water uptake and evapotranspiration are predicted. 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, water uptake, biomass production and nitrogen dynamics equations.

DETAILED DESCRIPTION OF THE PROCESSES IN SALTMED

The first version of the SALTMED model has been described in detail in Ragab (2002) with some examples of applications. The SALTMED model includes the following key processes: evapotranspiration, plant water uptake, water and solute transport under different irrigation systems, nitrogen dynamics and dry matter and biomass production. A brief description of the above mentioned processes will be given in the following sections.

Evapotranspiration

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

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

(1a)

where 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, (^oC), Δ is the slope of the saturated vapour pressure curve, (kPa $^oC^{-1}$), γ is the psychrometric constant, 66 Pa $^oC^{-1}$, 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 ET_o here is for short well-watered green grass. In this formula, a hypothetical reference crop with an assumed height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23 was considered.

In presence of stomata/canopy surface resistance data, one could use the widely used equation of Penman-Monteith (1965) in the following form:

$$\lambda E_p = \frac{\Delta R_n + \rho C_p \frac{(e_s - e)}{r_a}}{\Delta + \gamma \frac{(1 + r_s)}{r_a}} \qquad (1b)$$

where "r_s" and "r_a" are the bulk surface and aerodynamic resistances (s m^{-1}). The r_s can be measured or calculated from environmental and meteorological parameter or from the leaf water potential and ABA.

In the absence of meteorological data, and if Class A pan evaporation data are available, the SALTMED model can use this data to calculate ET_o according to the FAO (1998) procedure. The model can also calculate the net radiation from solar radiation, according to the FAO (1998) procedure, if net radiation data are not available. The crop evapotranspiration ET_c is calculated as:

$$ET_c = ET_o(K_{cb} + K_e)$$

(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, (the crop coefficient) 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 (1998). K_{cb} and K_c are adjusted according to FAO (1998) for wind speed and relative humidity if different from 2 m s^{-1} and 45%, respectively. The SALTMED model runs with a daily time step and uses K_{cb} and K_e. These parameter values are not universal and their values differ according to climatic conditions and other factors.

Calculating the stomata conductance from the ABA concentration

The modelling approach is based on Tardieu et al. (1993).

$gs = gs_{minimum} + \alpha * Exp(ABA * \beta * Exp(\sigma * \Psi_l))$

(3)

gs = stomata conductance, mole m^{-2} sec^{-1}

$gs_{minimum}$ = mimimum Stomata conductance, (*mole* m^{-2} sec^{-1} *)*

ABA = Absecic Acid concentration, daily values, *(mmole* m^{-3}*)*

Ψ_l = leaf water potential in M pa, daily values, *(Mpa)*

α, β, σ are fitting parameters, default values are :

Alpha, α	Beta, β	Sigma, σ
0.184	-2.69	-0.183

ABA and Ψ_l are given as daily values.

Calculating the stomata conductance from regression equation

The modelling approach for stomatal conductance is based on the multiplicative model described by Jarvis (1976) and modified by KÖrner et al. (1994).

Based on Jarvis (1967) and KÖrner (1994):

$g_s = g_{smax} * f(VPD) * f(T) * F(SW) * f(PAR)$

(4)

gs_{max} = Maximum Stomata conductance

f (VPD) is the relative effect of the VPD on stomata conductance, f(T) is the relative effect of the temperature on stomata conductance

f (SW) is the relative effect of the soil water content, SW on stomata conductance

f(PAR) is the relative effect of the photosynthetic active radiation, PAR on stomata conductance

The sum of $\sum f(VPD) * f(T) * F(SW) * f(PAR) \leq 1$

$f(VPD) = 1 - [(VPD\ min - VPD) / (VPD\ min - VPD\ max)]$

VPD is calculated on daily basis from temperature and relative humidity, RH data given as daily values in the input file of the climate data.

VPD min and VPD max are User input values

$F(T) = 1 - [(T - Tminimum) / (Toptimum - T\ minimum)]^2$

T is daily average Temperature given as input in climate data file

Tminimum and Toptimum are user input, ^oC

f(SW) = 0 if soil water content, θ is $\leq$ soil water content at wilting point θ_{WP}

$f(SW) = [(\theta - \theta_{WP}) / (\theta_{fc} - \theta_{WP})]$ if $\theta_{WP} < \theta < \theta_{FC}$

$f(SW) = 1$ if $\theta_{FC} < \theta < \theta_{SAT}$

θ is the average root zone soil water content and can be obtained from the model run as average values of the fully rooted squares, θ_{WP}, θ_{FC}, θ_{SAT} are soil water content at wilting point, at field capacity and at saturation (or porosity).

F (PAR) = 1 - exp (-α *PFD), α is a coefficient, PFD is photons flux density in micromole m^{-2} sec^{-1}.

Plant water uptake in the presence of saline water

The Actual Water Uptake Rate

The formula adopted in the SALTMED model is that suggested by Cardon and Letey (1992), which determines the water uptake S (d^{-1}) as:

$$S(z,t) = \left[\frac{S_{max}(t)}{1 + \left(\frac{a(t)h + \pi}{\pi_{50}(t)} \right)^3} \right] \lambda(z,t) \qquad (5)$$

where

λ (z) = 5/3L for $z \leq 0.2L$ (6)

= 25/12L * (1 - z/L) for $0.2L < z \leq L$ (6a)

= 0.0 for $z > L$ (6b)

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; π_{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%.

The maximum water uptake S_{max} (t) is calculated as:

$S_{max}(t) = ET_o (t)* K_{cb} (t)$ (7)

The values of h_{50} and π_{50} can be obtained from experiments or from literature such as FAO (1992).

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:

Root depth (t) =[Root $depth_{min}$+(Root $depth_{max}$ - Root $depth_{min}$)]*K_c (t)/$K_{c\ max}$ (8)

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

The rooting width

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

Root width (t) = [Root width / Root depth] ratio * root depth (t)

(9)

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. During the growth, new roots enter new grid cells.

The model then calculates the water uptake only from those cells with roots. The model grid cells are identified by 0, 1 or 2. The value of 0 is associated with cells with no roots and 1 for cells fully occupied with roots and 2 for cells with partial root presence. The model produces a data file showing the two –dimensional root distribution for every day of the simulation.

The Relative Crop Yield, RY

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

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

(10)

where x, z are the horizontal and vertical coordinates of each grid cell that contain roots, respectively.

The Actual Yield, AY

The AY is obtainable by:

$$AY = RY * Y_{\max}$$

(11)

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

The other option to obtain the AY is by calculating the daily biomass production and obtaining the AY from the harvest index times the total dry matter (see the relevant section on crop growth and dry matter).

Water and solute flow

The water flow in soils was 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:

$$q = -K(h)\frac{\delta H}{\delta Z} \qquad (12)$$

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:

$$H = \psi + Z$$

(13)

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:

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

(14)

where θ is volume wetness; *t* is the time; *z* is the depth; *K(θ)* 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 is also determined by diffusion and hydrodynamic dispersion. If the latter effects are negligible, solute flow by convection can be formulated as (Hillel, 1977):

$$J_c = qc = \bar{v}\theta c$$

(15)

where J_c is the solute flux density; *q* is the water flux density of the water; *c* the concentration of solute in the flowing water and $\bar{v}$ is the average velocity of the flow. The rate of a

Diffusion of a solute (J_d) in bulk water at rest is related, by Fick's law, to the concentration gradient as:

$$J_d = D_o(\partial c/\partial x)$$

(16)

where D_0 is the diffusion coefficient.

In soil, the diffusion coefficient (D_s) is decreased due to the fact that the liquid phase occupies only a fraction of the soil volume, and also due to the tortuous nature of the path. It can therefore be expressed according to the following equation:

$$D_s = D_0\theta\xi \qquad (17)$$

$$\xi = \theta^{7/3} / \theta_s{}^2$$

(18)

where ξ is the tortuosity, an empirical factor smaller than unity, which can be expected to decrease with decreasing θ as shown in Equation 18 (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:

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

(19)

where α is an empirical coefficient.

By the combination of the diffusion, the dispersion and the convection the overall flux of solute can be obtained as:

$$J = -(D_h + D_s)(\partial c/\partial x) + \bar{v}\theta c \qquad (20)$$

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

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

(21)

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 co-ordinates 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 co-ordinates 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:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\theta)\frac{\partial\psi}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial(\psi + z)}{\partial z}\right] \qquad (22)$$

where *x* is the horizontal co-ordinate; *z* is the vertical-ordinate (considered to be positive downward); K(θ) 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:

$$D_{ij} = \lambda_T|V|\delta_{ij} + (\lambda_L - \lambda_T)V_iV_j / |V| + D_s(\theta) \qquad (23)$$

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., δ_{ij} =1 if i = j and δ_{ij} = 0 if i ≠ j); V_i and V_j are the *i*th and *j*th components of the average interstitial flow velocity V, respectively; $V = (V^2_x + V^2_z)^{1/2}$ and $D_s(\theta)$ is the soil diffusion coefficient as defined in Equation 16.

If one considers only two dimensions and substituting D_{ij}, the salt flow equation becomes:

$$\frac{\partial(C\theta)}{\partial t} = \frac{\partial}{\partial x}\left(D_{xx}\frac{\partial C}{\partial x} + D_{xz}\frac{\partial C}{\partial z} - q_x C\right) + \frac{\partial}{\partial z}\left(D_{zz}\frac{\partial C}{\partial z} + D_{zx}\frac{\partial C}{\partial x} - q_z C\right)$$

(24)

In the model, sprinkler, flood and basin irrigation are described by one-dimensional flow equations (e.g. Eqs 14 and 21); furrow and trickle line source are described by 2-dimensional equations (e.g. Eqs 22 and 24); trickle point source is described by cylindrical flow equations, obtained by replacing x by the radius "r" and rearranging Equations 22 and 24 as given by Bresler (1975) and by Fletcher Armstrong and Wilson (1983). The water and solute flow equations were solved numerically using a finite difference explicit scheme (Ragab et al., 1984).

Soil hydraulic parameters

Solving the water and solute transport equations requires both the soil water content-water potential relation and the soil water potential-hydraulic conductivity relation. They were taken according to van Genuchten (1980) as:

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

(25)

$$K(h) = K_s K_r(h) = K_s Se^{1/2} [1- (1- Se^{1/m})^m]^2$$

(26)

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

Equations 25 and 26 were used after being re-arranged to obtain the soil water potential and hydraulic conductivity as functions of effective saturation as:

$$S_e = (\theta - \theta_r) / (\theta_s - \theta_r)$$

(27)

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

(28)

$$K(S_e) = K_s Se^{\lambda} [1-(1- S_e^{1/m})^m]^2$$

(29)

Based on pedotransfer functions, values of θ_r, θ_s, λ, 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 are given in the data base. These values, and others 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.

Drainage Free drainage at the bottom of the root zone is considered.

Crop growth, biomass production and yield

The approach used is based on Eckersten and Jansson (1991).
The increase in Biomass (Δ q in g m^{-2} day^{-1}) = Net Assimilation "NA"
The net Assimilation "NA" = Assimilation "A" – Respiration losses "R"
Assimilation rate "A" per unit of area = E* I* f (Temp)* f (T)*f (Leaf-N)
(30)
where E is the photosynthetic efficiency in g dry matter/MJ; I is the radiation input = Rs (1- e^{-k*LAI}), Rs is global radiation in MJ m^{-2} day^{-1}; k is extinction coefficient and LAI is the Leaf Area Index in m^2 m^{-2};; Rs is given in climate data, LAI is interpolated in SALTMED.

The transpiration stress factor is taken as the ratio of actual plant water uptake to the potential water uptake. The temperature stress is taken as the deviation of the average temperature for a given day from the optimum temperature for the growth. The leaf nitrogen stress is taken as the deviation of the leaf nitrogen content of a given day from the optimum leaf nitrogen content.

Calculating soil temperature from air temperature

The top soil layer is the most biologically active layer where most of the organic matter decomposition and mineralization takes place. The microbial activity is affected by the soil temperature of this layer, which was found to be correlated to air temperature. The approach used here is to infer the soil temperature of the ploughing layer from the air temperature based on the work of Kang et al. (2000) and Zheng et al. (1993).
For air temperature "A" and soil temperature "T", the relation can be described as:

For $A_j > T_{j-1}(z)$:

$$T_j(z) = T_{j-1}(z) + [A_j - T_{j-1}(z)] * \mathrm{Exp}[-z((\pi / (k_s * p))^{0.5}] * \mathrm{Exp}[-k(LAI_j + litter_j)]$$
(31)

For $A_j \leq T_{j-1}(z)$:

$$T_j(z) = T_{j-1}(z) + [A_j - T_{j-1}(z)] * \mathrm{Exp}[-z((\pi / (k_s * p))^{0.5}] * \mathrm{Exp}[-k(litter_j)]$$
(32)

where A_j is the average air temperature at day " j " , in °C ; A is calculated from Tmin and Tmax, which are given as input in the climate data file; $T_{j-1}(z)$ is the soil temperature at day " j-1" previous day at depth "z " below soil surface, in °C; $T_j(z)$ is soil temperature at day "j "and depth "z "below soil surface, in °C; Exp $[-z((\pi / (ks * p))^{0.5}]$ is a damping ratio; k_s is the thermal diffusivity as a function of soil water, air and mineral content, in m^2 s^{-1} ; $k_s =$ (thermal conductivity/(bulk density* specific heat capacity)); P is the period of either diurnal or annual temperature variation; z is depth, in meters; LAI is the leaf area index, calculated already in the model on daily basis; litter fraction is given as user input. Soil thermal parameters are based on Marshall et al. (1996) and used as default values in the model database.

Soil nitrogen dynamics and nitrogen uptake

These are based on the SOIL N model of Johnsson et al. (1987). The following processes were implemented in the SALTMED model: mineralization, immobilization, nitrification, denitrification, leaching and plant N uptake.

Nitrogen input included dry and wet deposition; incorporation of crop residues; manure application; chemical fertilizer application, dry or with irrigation water as fertigation.

Mineralisation of humus, N_h (z), is calculated as a first-order rate:

$$N_{h\rightarrow NH_4^+}(z) = k_h e_t(z) e_m(z) N_h(z)$$

(33)

where k_h is the specific mineralization constant and $e_t(z)$ and $e_m(z)$ are response functions for soil temperature and moisture, respectively.

$N_{h\rightarrow NH_4^+}$ is in g nitrogen m^{-2} day^{-1}, k_h is in day^{-1}, e_t and e_m are dimensionless, N_h (z) is in g nitrogen m^{-2}.

Decomposition of soil litter carbon, C_l (z), is a function of a specific rate constant (k_l), temperature and moisture:

$$C_{l(d)}(z) = k_l e_t(z) e_m(z) C_l(z)$$

(34)

$C_{1\,(d)}$ (z) is in g carbon m^{-2} day^{-1}; k_l in day^{-1}, e_t and e_m are dimensionless and C_l (z) is in g carbon m^{-2}.

The relative amounts of decomposition products formed:

$$C_{l\rightarrow CO_2}(z) = (1 - f_e) C_{l(d)}(z)$$

(35)

$$C_{l\rightarrow h}(z) = f_e f_h C_{l(d)}(z)$$

(36)

and

$$C_{l\rightarrow l}(z) = f_e (1 - f_h) C_{l(d)}(z)$$

(37)

are governed by a synthesis efficiency constant (f_e) and a humification factor (f_h).

$C_{l\rightarrow CO_2}$, $C_{l\rightarrow h}$ and $C_{l\rightarrow l}$ are in g carbon m^{-2} day^{-1}, $C_{l\,(d)}$ is in g carbon m^{-2}, f_e and f_h are dimensionless.

From Eqs (34), (36) and (37), net mineralization or immobilisation of nitrogen in litter (N_l (z)) is determined:

$$N_{l\rightarrow NH_4}(z)=\left[\frac{N_l(z)}{C_l(z)}-\frac{f_e}{r_o}\right]C_{l(d)}(z)$$

(38)

where $N_{l\rightarrow NH_4}$ is in g nitrogen m^{-2} day^{-1}, N_l is in g nitrogen m^{-2}, C_l is in g carbon m^{-2}, fe and r_o (the C-N ratio of microorganisms and humified products) are dimensionless.

The transfer rate of ammonium to nitrate:

$$N_{NH_4\rightarrow NO_3}(z)=k_n e_t(z)e_m(z)\left[N_{NH_4}(z)-\frac{N_{NO_3}(z)}{\eta_q}\right]$$

(39)

depends on the potential rate (k_n), which is reduced as the nitrate-ammonium ratio (η_q) is approached.

$N_{NH_4\rightarrow NO_3}$ is in g nitrogen m^{-2} day^{-1}, N_{NH_4} and N_{NO_3} are in g nitrogen m^{-2}, k_n is in day^{-1}, and η_q, e_t and e_m are dimentionless.

$$e_t(z)=Q_{10}^{\left[\frac{T(z)-t_o}{10}\right]}$$

(40)

where T(z) is the soil temperature for the layer, t_o is the base temperature at which e_t(z) equals 1 and Q_{10} is the factor change in rate with a 10-degree change in temperature.

$$e_m(z)=e_s+(1-e_s)\left[\frac{\theta_s(z)-\theta\ (z)}{\theta_s(z)-\theta_{ho}(z)}\right]^m \qquad \theta_s(z)\geq\theta(z)>\theta_{ho}(z)$$

(41)

$$e_m(z)=1 \qquad \theta_{ho}(z)\geq\theta(z)\geq\theta_{lo}(z)$$

(41a)

$$e_m(z)=\left[\frac{\theta(z)-\theta_w(z)}{\theta_{lo}(z)-\theta_w(z)}\right]^m \qquad \theta_{lo}(z)>\theta(z)\geq\theta_w(z)$$

(41b)

where θ(z) is the saturated water content, θ_{ho}(z) and θ_{lo}(z) are the high and low water contents, respectively, for which the soil moisture factor is optimal and θ_w(z) is the minimum water content for process activity, the coefficient e_s defines the relative effect of moisture when the soil is completely saturated and m is an empirical constant.

The two thresholds, defining the optimal range are calculated as:

$$\theta_{lo}(z)=\theta_w(z)+\Delta\theta_l$$

(42)

$$\theta_{ho}(z) = \theta_s(z) - \Delta\theta_2$$
(42a)
where $\Delta\theta_1$ is the volumetric range of water content where the response increases and $\Delta\theta_2$ is the corresponding range where the response decreases, the water content is in m^3m^{-3}, soil temperature is in ^oC and e_t and e_m are dimensionless.

Plant nitrogen uptake

A logistic uptake curve is used to define the cumulative potential N demand during the growing season

$$\int u(t)dt = \frac{u_a}{1 + \frac{u_a - u_b}{u_b} e^{-u_c t}}$$
(43)
where u_a is the potential annual N uptake, u_b and u_c are shape parameters and t is days after the start of the growing season, u_a is in g nitrogen m^{-2} $season^{-1}$.

Daily uptake of nitrate is then calculated from the relative root fraction in the layer ($f(z)$), the proportion of total mineral N as nitrate and the derivative of the growth curve (u). u is obtained from Eq. 11 on daily basis expressed as gram nitrogen m^{-2} day^{-1}, $N_{NO_3}(z)$ and $N_{NH_4}(z)$ are in gram nitrogen m^{-2}.

$$N_{NO_3 \to p}(z) - MIN \quad \text{of} \quad f_r(z)\frac{N_{NO_3}(z)}{N_{NO_3}(z) + N_{NH_4}(z)}u$$
(44)

and

$$f_{ma} N_{NO_3}(z)$$

The denitrification rate is expressed as a power function which increases from a threshold ($\theta_d(z)$) and is maximum at saturation ($\theta_s(z)$), where d is an empirical constant.

$$e_{md}(z) = \left[\frac{\theta(z) - \theta_d(z)}{\theta_s(z) - \theta_d(z)}\right]^d \tag{45}$$

The denitrification rate for each layer depends on a potential denitrification rate ($k_d(z)$), the soil water/aeration statue ($e_{md}(z)$) and the temperature factor ($e_t(z)$) used for the biologically-controlled processes.

$$N_{NO_3 \to}(z) = k_d(z) e_{md}(z) e_t(z) \left[\frac{[N_{NO_3}(z)]}{[N_{NO_3}(z)] + c_s}\right] \tag{46}$$

$N_{NO_3 \rightarrow}$ (z) and k_d (z) are in g nitrogen m^{-2} d^{-1}, $N_{NO_3}(z)$ is in g nitrogen m^{-2}, C_s is in mg l^{-1}, e_t and e_{md} are dimensionless. Parameter value ranges are reported in Johnsson et al. (1987) and Wu et al. (1998).

MODEL APPLICATION

Figure 2 shows examples of model application. The early version of SALTMED model has been successfully tested against field data of tomato grown in Syria and Egypt for five seasons 2000-2002 in both countries. The results are published in Ragab (2005). Since then, the model underwent several modifications and improvements. The model has recently been applied successfully on a sugar cane field experiment in Iran (Golabi et al., 2009), on a cotton plantation in Greece (Kalfountzos et al., 2009) and on several field crops in the north east of Brazil (Suzana et al., 2010). The newest version of the SALTMED model "SALTMED 2009" has been tested against field data of tomato and potato from Italy, Crete and Serbia. Sub-surface drip irrigation, furrow irrigation and sprinkler irrigation were applied as full or deficit irrigation including PRD using subsurface twin tube drip-lines and alternate furrows. The model was able to successfully simulate dry matter production, final yield, soil moisture and nitrogen profiles. The results will be given in a follow up paper.

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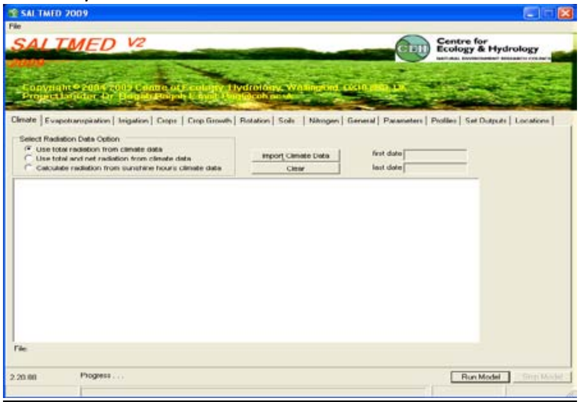
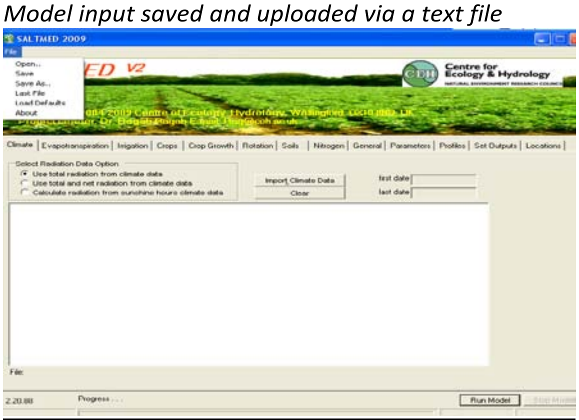
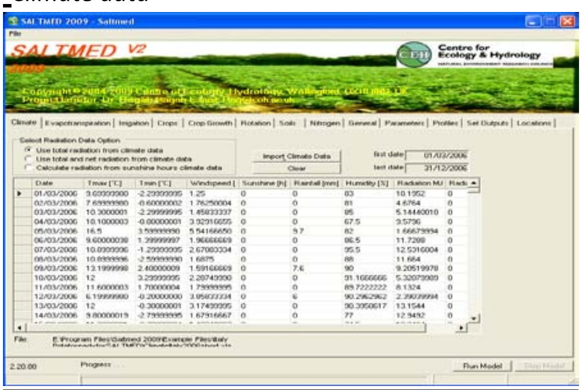
Main input tabs



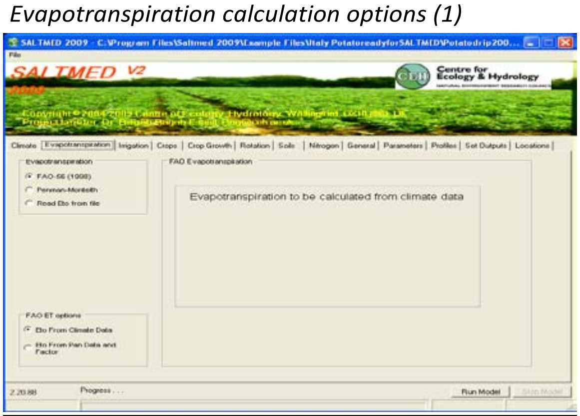
Model input saved and uploaded via a text file



_*Climate data*



Evapotranspiration calculation options (1)



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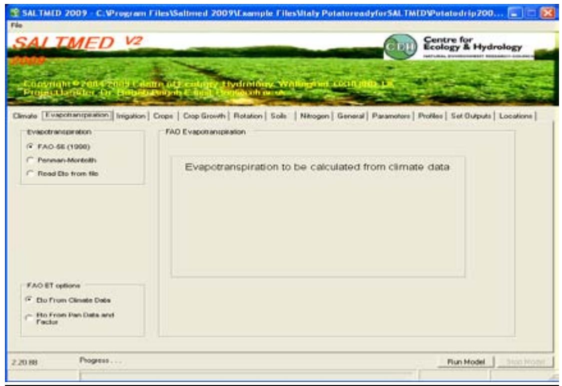

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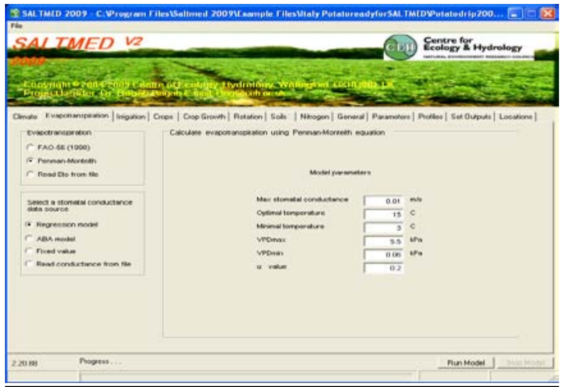
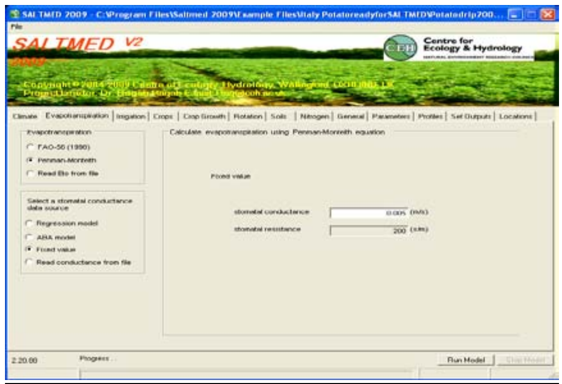
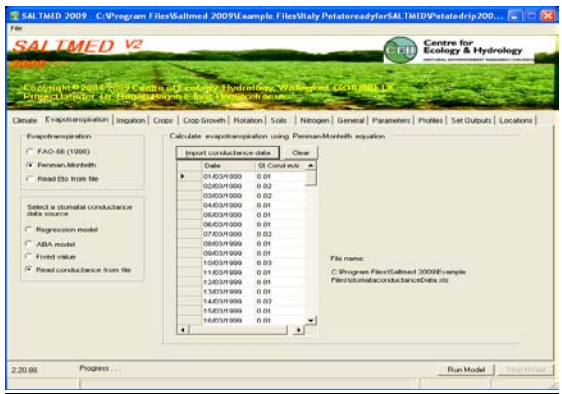


Evapotranspiration calculation options (4)



Evapotranspiration calculation options (5)



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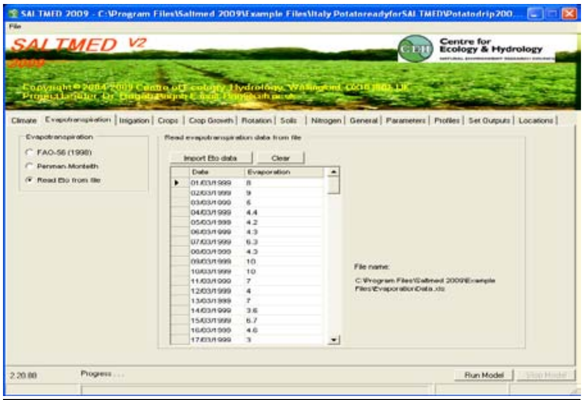

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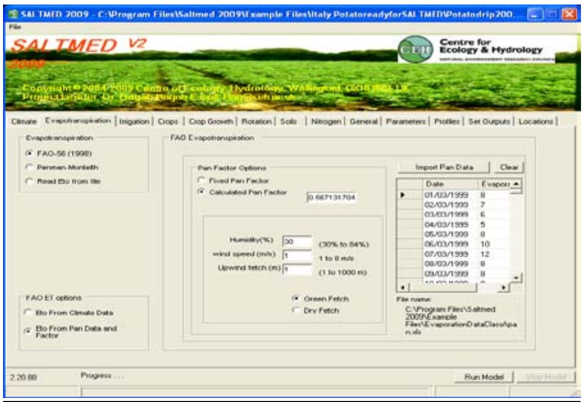
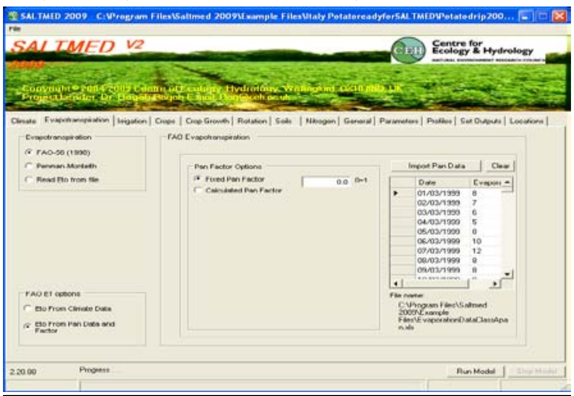
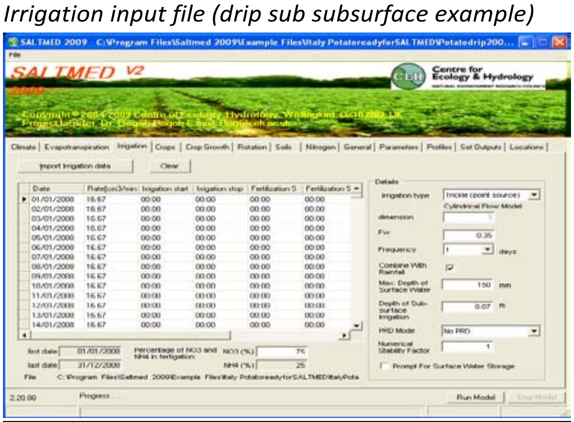


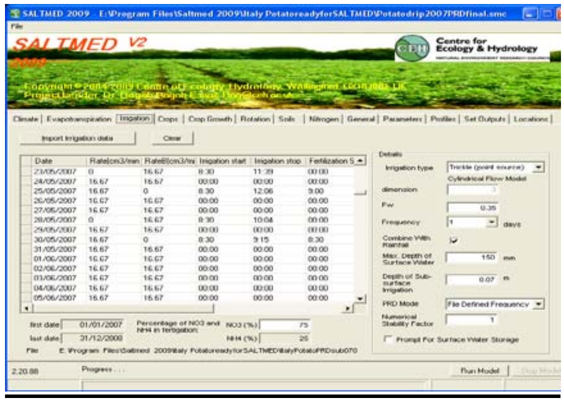
Evapotranspiration calculation options (8)



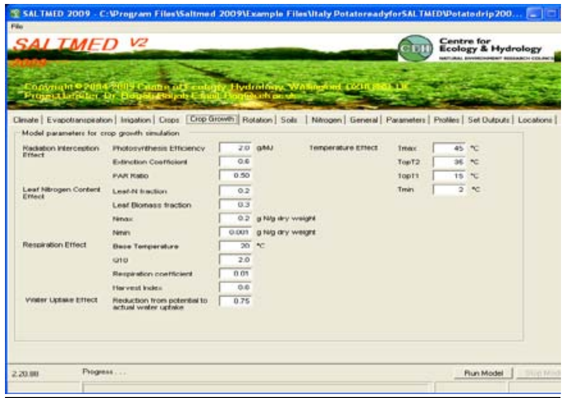
Irrigation input file (drip sub subsurface example)



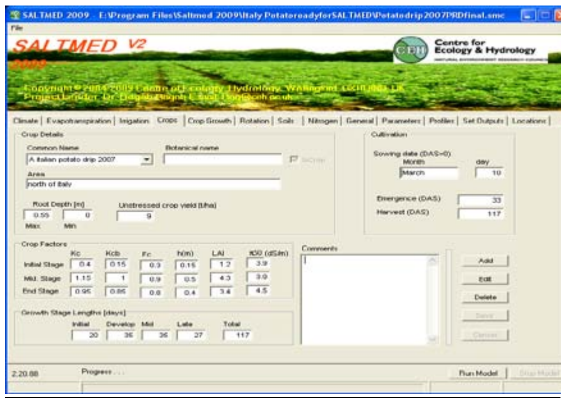
Irrigation input file (drip sub sub-surface PRD)



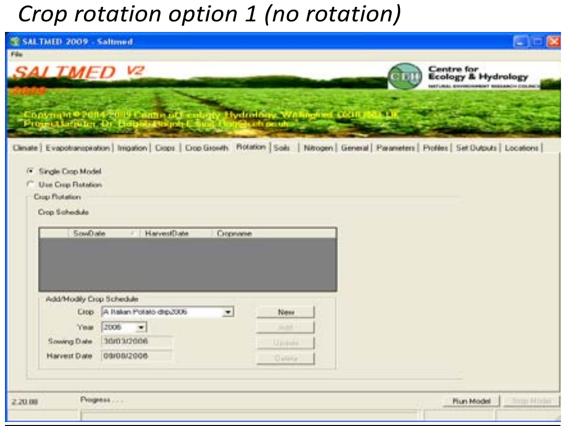
Crop growth input parameters (1)



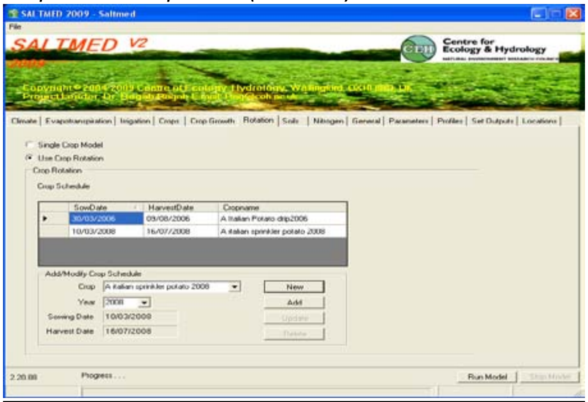
Crop growth input parameters (2)



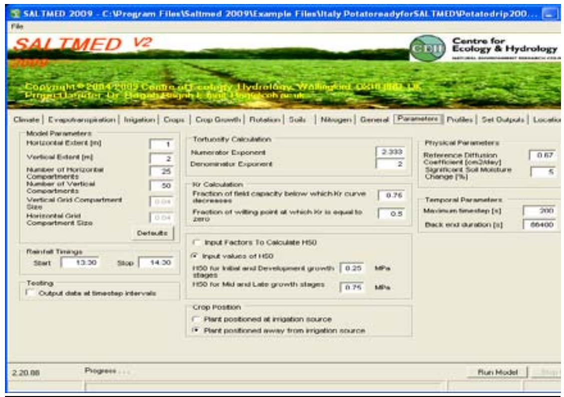
Crop rotation option 1 (no rotation)



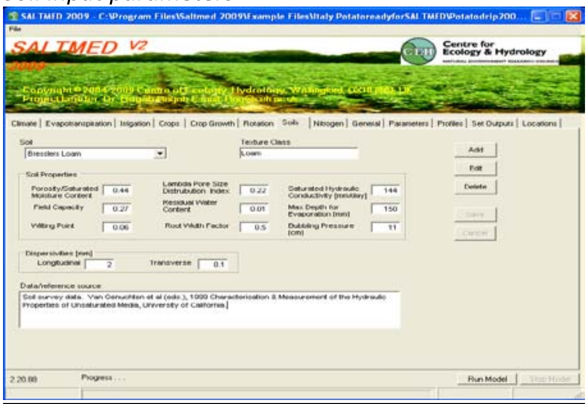
Crop rotation option 2 (rotation)



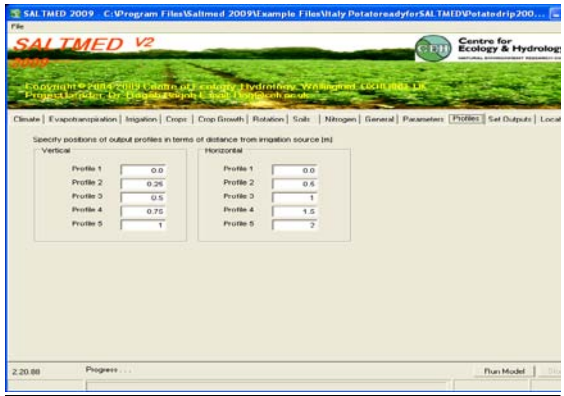
Model input parameters



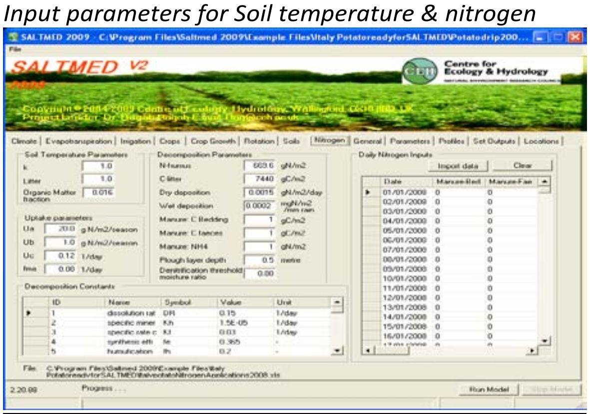
Soil input parameters



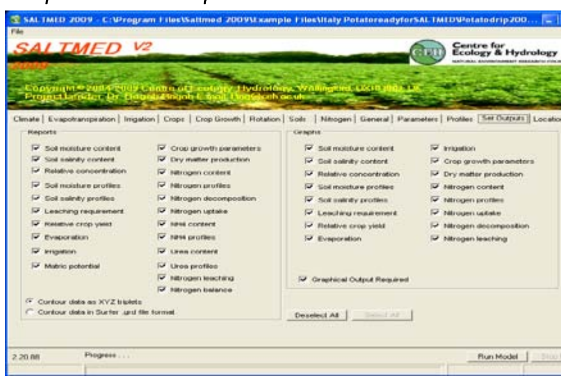
Options for plotting output variable profiles



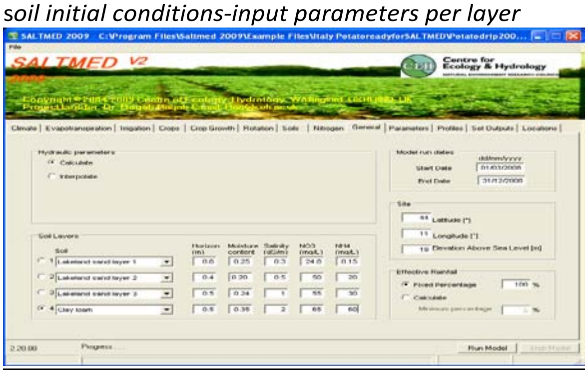
Input parameters for Soil temperature & nitrogen



Output selection options



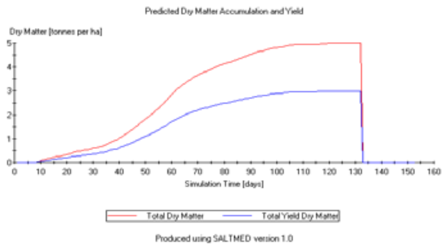
soil initial conditions-input parameters per layer



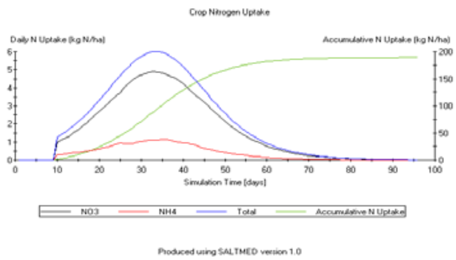
Output selection folder

Figure 1. SALTMED 2009 input frames

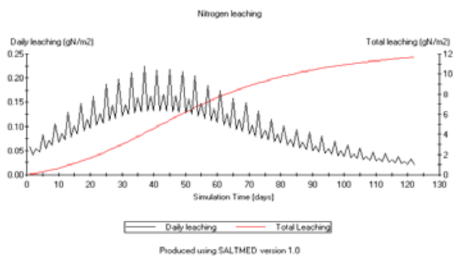
Output example of Dry matter



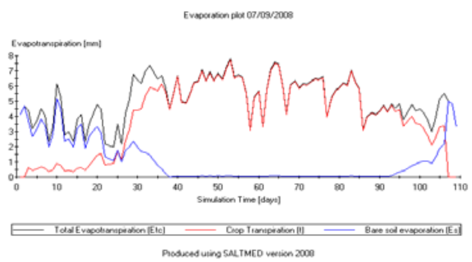
Output example of plant –N uptake



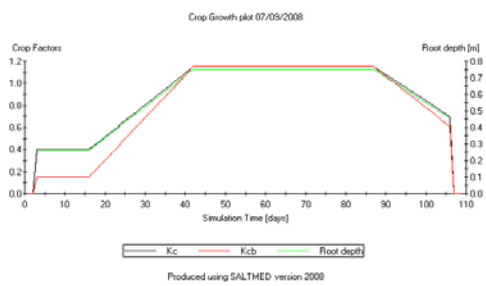
Output example of N- Leaching



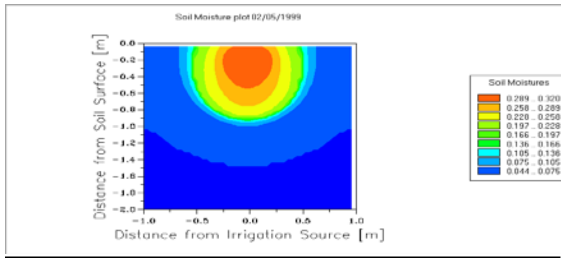
Output *example of Evapotranspiration*



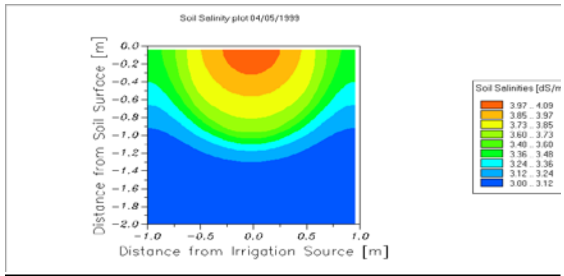
Output *example of crop growth parameters*



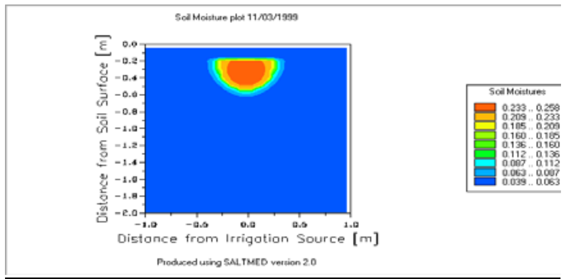
Output example of soil moisture under drip irrigatio



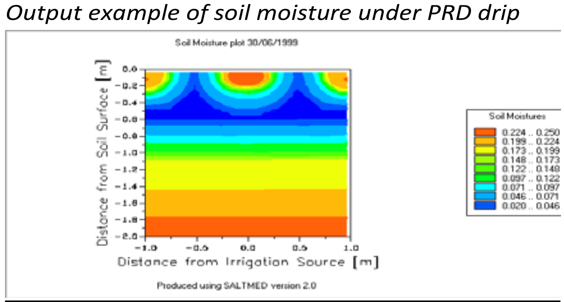
Output example of soil salinity under drip irrigation



Output example of soil moisture, subsurface drip



Output example of soil moisture under PRD drip



Output example of soil moisture, PRD subsurface drip

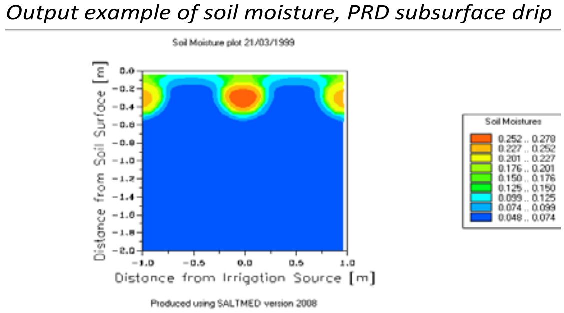


Figure 2. SALTMED 2009 output examples