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Water Management in the Next Century

Subsurface Drainage Simulation Models
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Actes de l'atelier
La Haye, Pays-Bas, 4 et 5 septembre 1993

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Session 1 - *1re session*

Simulation Modeling of Drained Soils

Modélisation des sols drainés

A NUMERICAL MODEL FOR THE ANALYSIS OF SOIL AMELIORATION UNDER THE CONDITION OF EQUALLY SPACING TRENCHES

J.Z. YANG, W.Z. ZHANG
Wuhan University of Hydraulic and Electric Engineering

ABSTRACT. In North China, there is a large area of saline soil mainly caused by excessive irrigation and poor ground water management. In these area, ground water is of high salt content and the water table depth is less than that required for salinity control and the intensive accumulation of salt usually occurs in spring and early summer. Hence, the soil amelioration and salt control in the area is crucial in order to get high crop products. The principle methods to improve saline soil and secure normal growth of crop in these field are: (1). planting paddy rice and ponded leaching; (2). improving the irrigation water management to keep salt content in the top soil layer less than the crop tolerance; (3). applying fresh water from streams and canals mixed with saline water pumping from tube wells.

To study the process of desalinization and the salt movement under different water management, a numerical model is proposed to solve the unsaturated-saturated soil water flow and solute transport. The model is tested by an experiment and used to simulate salt distribution under the condition of ponded leaching with different irrigation schedules.

GOVERNING EQUATION AND NUMERICAL MODEL

Experiments carried out in laboratory (1) demonstrate that when solute is transported in unsaturated and saturated soils, immobile water phase does exist in dead end pores, unconnected and semi-connected pore. Due to molecular diffusion the mass exchange occurs between mobile and immobile water phase. The governing equation representing solute transport in unsaturated and saturated soil can he written as:

$$\frac{\partial \theta_{im} C_{im}}{\partial t} + \frac{\partial \theta_m C_m}{\partial t} = \frac{\partial}{\partial x_i}\left[\theta_m D_{ij} \frac{\partial C_m}{\partial x_j}\right] - \frac{\partial}{\partial x_i}[q_i C_m] \qquad (1)$$

$$\frac{\partial \theta_{im} C_{im}}{\partial t} = \alpha\,(C_m - C_{im}) \qquad (2)$$

Where θ_{im}, and θ_m, are the immobile and mobile water content($\theta_{im} + \theta_m = \theta$), respectively, θ is the volumetric water content, C_m, and C_{im} the concentration of immobile and mobile water, D_{ij} the component of hydrodynamic dispersion coefficient tenor, q_i the component of water flux vector, α the mass transfer coefficient.

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When dispersion dominates in Eq.(1), the equation is parabolic in character, which can be solved successfully by finite difference or finite element method. When convection dominats the character of the equation (1) changes to hyperbolic. The method of characteristics is effective for solving this kind of equation. The combined use of finite element method and the method of characteristics is effective for both convection-dominated and dispersion-dominated problems. Expanding the second term of right hand side in Eq.(1), the following equation results:

$$\theta_m \frac{\partial C_m}{\partial t} + \frac{\partial \theta_{im} C_{im}}{\partial t} = \frac{\partial}{\partial x_i}\left[\theta_m D_{ij} \frac{\partial C_m}{\partial x_i}\right] - q_i \frac{\partial C_m}{\partial x_i} \tag{3}$$

Representing $\partial C_m/\partial t$ in Eq.(3) as concentration change in time of point y moving at velocity V and rearranging, yields:

$$\theta_m \left.\frac{\partial C_m}{\partial t}\right|_y + \frac{\partial \theta_{im} C_{im}}{\partial t} = \frac{\partial}{\partial x_i}\left[\theta_m D_{ij} \frac{\partial C_m}{\partial x_j}\right] - \left[q_i - \theta_m \frac{dx_i}{dt}\right] \frac{\partial C_m}{\partial x_i} \tag{4}$$

Where dx_i/dt_t is the velocity of moving point y. When y is taken as a fluid particle, the velocity of the moving point is the same as velocity q_i/θ_m,. That is:

$$q_i/\theta_m = dx_i/dt \tag{5}$$

Substituting above equation in (4) yields:

$$\theta_m \frac{DC_m}{Dt} + \frac{\partial \theta_{im} C_{im}}{\partial t} = \frac{\partial}{\partial x_i}\left[\theta_m D_{ij} \frac{\partial C_m}{\partial x_j}\right] \tag{6}$$

Where DC_m/Dt represents material derivative, here C_m, no longer represents concentration at a point in space, but rather concentration of a fluid particle moving at velocity V.

For two-dimensional Problem Eq.(5) can be written as:

$$\begin{aligned} \theta_m \frac{DC_m}{Dt} + \frac{\partial \theta_{im} C_{im}}{\partial t} &= \frac{\partial}{\partial x}\left[\theta_m D_{xx} \frac{\partial C_m}{\partial x} + \theta_m D_{xz} \frac{\partial C_m}{\partial z}\right] + \\ &\quad \frac{\partial}{\partial z}\left[\theta_m D_{zx} \frac{\partial C_m}{\partial x} + \theta_m D_{zz} \frac{\partial C_m}{\partial z}\right] \end{aligned} \tag{7}$$

Where:

$$\begin{aligned} \theta_m D_{xx} &= \theta_m (\alpha_L V^2_x + \alpha_T V^2_z) / V + D_m \\ \theta_m D_{xz} &= \theta_m D_{zx} = \theta_m (\alpha_L - \alpha_T) V_x V_z / V \\ \theta_m D_{zz} &= \theta_m (\alpha_L V^2_z + \alpha_T V^2_x) / V + D_m \end{aligned} \tag{8}$$

D_m, is the molecular diffusion coefficient in porous media, α_L, α_T the longitudinal and transverse dispersivity, respectively. The Galerkin finite element method is used to determine the approximate solution of Eq. (7). The nodal points are taken as fluid particles. The trial function has the form:

$$\tilde{C}_m = \sum_{j=1}^{n} \Phi_j \, C_{mj}(t) \tag{9}$$

Where Φj is the basic function, C_{mj} the time-dependent concentration at the jth point of the discrete system and N the total number of nodes.

Substituting Eq. (9) into (7) and setting the resulting residual orthogonal to all the function Φj , we obtain:

$$\begin{aligned}
&\sum_{\beta}\sum_{j} \frac{1}{4\Delta_\beta} C_{mj} \left[\overline{\theta_m D_{xx}}\, b_i b_j + \overline{\theta_m D_{xz}}\,(b_i d_j + b_j d_i) + \overline{\theta_m D_{zz}}\, d_i d_j\right] + \\
&\sum_{\beta} \left.\frac{DC}{Dt}\right|_i \frac{1}{3}\sum_{p} \theta_{mp} \frac{1+\delta_{ip}}{4} \Delta_\beta + \sum_{\beta} \left.\frac{\partial \theta_{im} C_{im}}{\partial t}\right|_i \frac{\Delta_\beta}{3} \qquad (10)\\
&= \sum_{\beta} \oint_{\Gamma_2^3} \left[\theta_m \left(D_{xx}\frac{\partial C_m}{\partial x} + D_{xz}\frac{\partial C_m}{\partial z} n_x + \theta_m \left(D_{zx}\frac{\partial C_m}{\partial x} + D_{zz}\frac{\partial C_m}{\partial z}\right) n_z\right]\Phi_i \, d\Gamma
\end{aligned}$$

where:

$$\overline{\theta_m D_{xx}} = \frac{1}{3} \sum_{p=i,j,k} \theta_m(h_p)\,(\alpha_L V^2{}_{xp} + \alpha_T V^2{}_{zp}) / V + D_o\, \alpha_m\, e^{\beta_M \theta(h_p)}$$

$$\overline{\theta_m D_{xz}} = \frac{1}{3} \sum_{p=i,j,k} \theta_m(h_p)\,(\alpha_L - \alpha_T)\, V_{xp} V_{zp} \;/ V \tag{11}$$

$$\overline{\theta_m D_{zz}} = \frac{1}{3} \sum_{p=i,j,k} \theta_m(h_p)\,(\alpha_T V^2{}_{xp} + \alpha_L V^2{}_{zp}) / V + D_o\, \alpha_m\, e^{\beta_m \theta(h_p)}$$

d_p, d_p are the element dimensions, Δ_β the element area.

Replacing the time derivative in Eq.(2) by difference and arranging yields:

$$\left.\frac{\partial \theta_{im} C_{im}}{\partial t}\right|_i \approx \frac{\theta_{im}\alpha}{\theta_{im} + Q\alpha\Delta t_k} C_{mi}^{k+Q} - \frac{\theta_{im}\alpha}{\theta_{im} + Q\alpha\Delta tk} C_{imi}^{k+Q} \tag{12}$$

$$C_{imi}^{k+1} \approx \frac{\alpha + \Delta t_k}{\theta_{im} + Q\alpha\Delta t_k} C_{mi}^{k+1} + \frac{\theta_{im} - \alpha\Delta t_k(1-Q)}{\theta_E + Q\alpha\Delta t_k} C_{imi}^{k} \tag{13}$$

Where Q is the time weighting factor, 0<Q<1.

Substitution of Eq. (13) into (10) leads to the following system of ordinary differential equation:

$$[D]\{C_m\} + [E]\left\{\frac{DC_m}{Dt}\right\} = \{F\} \tag{14}$$

Replacing material derivative DC_m/Dt by difference yields:

$$\frac{DC_m}{Dt} \approx \frac{C_{mi}^{k+1} - C_{mi}^{k}}{\Delta t_k} \tag{15}$$

Where C_{mi}^{k+1}, C_{mi}^{k} are the concentration of moving node i at time t^{k+1} and t^k, respectively.

Substituting Eq.(15) into (14) and rearranging:

$$([D] + [E]/\Delta t_k)\{C_m\}^{k+1} = [E]/\Delta t_k \{C_m\}^k + \{F\} \tag{16}$$

There are various methods to deal with the movements of nodes. The movement of finite element network can be determined as follows: A nodal point, located at position (x_i^k, z_i^k) at time t^k, will reach a new position (x_i^{k+1}, z_i^{k+1}) at time t^{k+1}, where:

$$x_i^{k+1} = x_i^k + \int_{t^k}^{t^{k+1}} V_x dt \qquad z_i^{k+1} = z_i^k + \int_{t^k}^{t^{k+1}} V_z dt \tag{17}$$

Then, adding and eliminating nodal points along boundary and check the shape of element. If the shape of element satisfies some proposed requirements, the concentration distribution can be obtained from the solution of Equation (16). Otherwise , the elements should be regularized or generated.

TESTING OF THE NUMERICAL MODEL

The experiment simulates leaching of soil between equally spaced ditches under the condition of drainage and irrigation. The spacing of partial-penetrated ditched is 2x300cm. A horizontal imperious barrier is located at a depth of 190cm. Infiltration water is applied at a constant rate over a width of 2xl72cm centered between the ditches. Water level in the ditches is maintained at a depth of 20cm. Because of symmetry, only a half of the cross section between ditches needs to be considered. The experiment is run in the laboratory in a soil tank having internal dimensions of 300cm in length, 200cm in height, and 30cm in thickness(Fig.1). A sieve net is attached to the lateral end of the tank from soil surface to a depth of 150cm and connected to a reservoir with an adjustable water level, which is used to simulate the drainage ditch. The infiltration systems consist of two plexiglass boxes having dimension of 30cm in width, 5cm in thickness and 88cm and 84cm in length, respectively. The boxes are connected to constant water level reservoir. The infiltration rate q is controlled by the head difference between the reservoir and the box. The remaining soil surface without infiltration is covered with a plastic membrane to prevent evaporation.

Prior to the experiment, a solution containing 15g/L NaCl was introduced slowly at the bottom of the soil tank. The water table was maintained 50cm above the bottom. The experiment began after a steady states had been reached.

During experiment, the following measurements were made: (1 the pressure head in the unsaturated zone; (2) the inflow and outflow volumes; (3) the piezometric head in the saturated zone; (4) the electric conductivity of soil water; and (5) the conductivity of inflow and outflow water.

Water flow and solute transport parameters are given in Table 1 and 2.

The velocity V_x, V_z in Eq. (17) are obtained from Darcy's law, that is:

$$V_x = -\frac{K(h)}{\theta}\frac{\partial h}{\partial x} \qquad V_z = -\frac{K(h)}{\theta}\left(\frac{\partial h}{\partial z} + 1\right) \tag{18}$$

The pressure head is obtained from water flow equation:

$$\left[\frac{\theta}{n}S_s + C(h)\right]\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] + \frac{K(h)}{\partial z} \tag{19}$$

Where: $K(h)$ is the hydraulic conductivity; n: the porosity; Ss the specific storage; $C(h)=d\theta/dh$, the specific moisture capacity. The air phase in the unsaturated zone is assumed to be continuous and connected to the atmospheric pressure when the atmospheric pressure is taken as a datum.

Eq.(17) is solved by finite element method. The resulted algebraic equation is:

$$([B] + [M]/\Delta t_k)\{h\}^{k+1} = ([M]/\Delta t_k)\{h\}^k + \{g\}^{k+1} \tag{20}$$

Where:

$$B_{ij} = \sum_{p=1}^{n} K(h_p)\int_{\Omega}\Phi_p\left(\frac{\partial\Phi_i}{\partial x}\frac{\partial\Phi_j}{\partial x} + \frac{\partial\Phi_i}{\partial z}\frac{\partial\Phi_j}{\partial z}\right)d\Omega$$

$$M_{ij} = \sum_{p=1}^{n}\left[\frac{\theta(h_p)}{n}S_s + C(h_p)\right]\int_{\Omega}\phi_p\,\phi_i\,\phi_j\,d\Omega \tag{21}$$

$$g_i = -\oint_{\Gamma_2} q\,\Phi_i\,d\Gamma - \sum_{p=1}^{n} K(h_p)\int_{\Omega}\Phi_p\frac{\partial\Phi_i}{\partial z}\,d\Omega$$

the iterative solution begins with the linear extrapolation:

$$h_i^{k+1} = h_i^k, \qquad k=0$$

$$h_i^{k+1} = h_i^k + \frac{\Delta t_k}{\Delta t_{k-1}}(h_i^k - h_i^{k-1}),\ k>0 \qquad i=1,\ldots,n \tag{22}$$

$$h_i^{k+1/2,\,l} = (h_i^{k+1,\,l} + h_i^k) \;/\; 2, \qquad l = 1,\, 2,\, \ldots$$

When:

$$\left| h_i^{k+1,\,l+1} - h_i^{k+1,\,l} \right| \le \varepsilon_1$$

or:

$$\left| h_i^{k+1,\,l+1} - h_i^{k+1,\,l} \right| \;/\; \left| h_i^{k+1,\,l+1} - h_i^k \right| \le \varepsilon_2 \tag{23}$$

Then:

$$h_i^{k+1} = h_i^{k+1,\,l+1} \tag{24}$$

else substituting $h_i^{k+1,\,l+1}$ into (22) until Eq. (23) is satisfied.

For the node i in the seepage face, we have:

$$-\left[K \frac{\partial h}{\partial x} n_x + K \left(\frac{\partial h}{\partial z} + 1 \right) n_z \right]\Bigg|_i > 0, \quad h_i = 0 \tag{25}$$

for the node i above the seepage face, we have:

$$-\left[K \frac{\partial h}{\partial x} n_x + K \left(\frac{\partial h}{\partial z} + 1 \right) n_z \right]\Bigg|_i = 0, \quad h_i < 0 \tag{26}$$

A characteristic value $CHARA_i$ is assigned for node i in the segment M, where seepage face may appears. When $CHARA_i = 0$, the node is considered to be in the seepage face and $CHARA_i = -1$, the node is not in the seepage face.

The characteristic value $CHARA_i^k$ is known at the time t^k. The boundary condition for the node along segment M may be taken as follows according to $CHARA_i^k$:

$$h_i^{k+1} = 0$$

for the conditon $CHARA_i^{k+1,\,l} = CHARA_i^k = 0$.

$$-\left[K \frac{\partial h}{\partial x} n_x + K \left(\frac{\partial h}{\partial z} + 1 \right) n_z \right]\Bigg|_i = 0$$

for the condition $CHARA_i^{k+1,\,l} = CHARA_i^k = -1$.

The pressure $\{h\}^{k+1,\,l}$ is obtained from Eq. (20). Then the following condition should be checked:

If $\mathrm{CHARA}_i^{k+1,l} = 0$ and $-K\left[\frac{\partial h}{\partial x} n_x + (\frac{\partial h}{\partial z} + 1) n_z\right]_i > 0$

then $\mathrm{CHARA}_i^{k+1,l} = 0$ else $\mathrm{CHARA}^{k+1,l} = -1$.

If $\mathrm{CHARA}_i^{k+1,l} < 0$ and $h_i^{k+1,l+1} > 0$

then $\mathrm{CHARA}_i^{k+1,l+1} = -1$ else $\mathrm{CHARA}_i^{k+1,l+1} = 0$.

The seepage face iteration is successful only if all the nodes in the segment M satisfy the condition

$\mathrm{CHARA}_i^{k+1,l+1} = \mathrm{CHARA}_i^{k+1,l}$.

The measured and calculated concentration evolution of some measured points and the hydraulic head profiles at different times are illustrated in figure 2 and figure 3. In general, the agreement of the numerical and the experimental results are fairly good.

SALT DISTRIBUTION UNDER CONDITION OF PONDED LEACHING AND CONSTANT INFILTRATION

For the preliminary application of the numerial model to the soil amelioration, the salt distribution is analysed fir equally spaced ditches under the condition of ponded leaching and constant infiltration. It is assumed that the depth of ditch is 2.5m, the distance between the ditches is 180 m. The initial ground water table os at the depth of 2.5m and the pressure head in the unsaturated zone is the steady profile. From the ground surface to the depth of 50cm is 10g/L. All the parameters used are taken from real field data.

For the situation of ponded leaching, the ponding process lasts for 5 days, when the soil is almost saturated, and then the evaporation begins. It is shown in the simulation that the water flow in the upper 2.5m of soil. Wether in the process of ponding or in soil water redistribution process, is approximately vertical. Only near the ditches (2.5 - 5 m) the velocity has the appreciable horizontal component. Before the upper 2.5m of soil gets saturated the depth of desalinization zone is approximately the same in whole soil. It indicates that on this period the ditch is not in action. When the leaching stops, the solute front near the ditch continues falling under the effect of ditch drainage. But in the middle between the ditches, the solute front moves upward with the effect of evaporation (Figure 4).

If the soil salinity is not too high, the salt sontent in the top soil layer can be kept at a level less than that of crop tolerance by choosing proper leaching quota (2). In the infiltration period the saline soil in the top layer is desalinized, and in the dry period without irrigation ground water is consumed mainly on evapotranspiration and the salt content above the water table redistributes in the process of evaporation. When the water content in the root zone drops to permissible lower limit or the salt content in the top soil layer exceeds the crop tolerance, irrigation and leaching water should be applied. The amount of irrigation water or the irrigation interval required can be worked out by numerical simulation. In the following example of numerical simulation the spacing and depth of ditches and soil condition are the same as the above one. The depth of leaching water used are 9cm, 13.5cm and 18cm, respectively. The simulated soil water concentration profile is shown in figure 5. For the simulation of small leaching quota (9cm), the soil water concentration profile is the same at the point near the ditch and in the middle between the ditches in the infiltration process or for 30 days of evaporation, which indicates that for small amount of irrigation the effect of ditch on soil water concentration distribution is negligible. It is seen from figure 5 that the more the irrigation water applied, the deeper the desalinization zone and the lower the salt content in top soil. Table 3 gives the salt content in the top 30cm soil layer. If the permissible salt content in the top soil is given, for instance 0.2%. From the Table we can determine the irrigation interval. For example, if the irrigation quota is 9cm, the salt content in top soil layer is 0.19% on 18 days after irrigation and 0.24% on 30 days. We can approximately determine, only from the permissible salt content, the irrigation interval is about 18 days.

Above discussion deal mainly with the solute movement under very simple irrigation and drainage condition. With the same model, we can determine the ditch spacing under different conditions of water management and vice versa.

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APPLICATION OF DRAINMOD FOR SIMULATING SOIL WATER REGIME IN THE COASTAL REGION OF NORTHERN GERMANY

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ABSTRACT. A simulation computer model proposed by Skaggs (1978 and 1980) was used to characterize the response of the soil water regime to the water management of a silty alluvial soil in northern Germany under different drainage intensities.

The comparison between the measured and predicted water table elevations show that the agreement is particularly better for the 7 m and 14 m spacing than for 28 m spacing, and during the winter months than for summer months. Subirrigation was used for short periods in summer, but the subirrigation data was not used in the model because of no measured data was available. But even with a 28 m drain distance the predicted groundwater was deep enough for agricultural operations in autumn and spring however for shorter times than at 14 m and 7 m drain distance.

The groundwater level was almost the same for 7m and 14 m drain spacing. But at 28 m it was about 10-20 cm higher. Without pipe drainage the groundwater level was too high in the spring and in the autumn and thereeupon no field working days resulted.

The results of a one year periods show that there were no significant differences on the drain discharge sum between 7 m, 14 m and 28 m drain distance. But the closer the drain distance the shorter the discharge periods, the higher the rate of discharge and the more the available field workings days.

***RESUME.** Application de DRAINMOD à la simulation du régime hydrique du sol dans la région côtière du nord de l'Allemagne.*

Le modèle DRAINMOD proposé par Skaggs (1978 et 1980) a été utilisé pour caractériser la réponse du régime de l'eau du sol à différents modes de gestion de l'eau sous différentes intensités du drainage dans un sol limoneux alluvial au nord de l'Allemagne.

La comparaison entre l'élévation de la nappe simulée et mesurée a montré une meilleure adéquation pour les espacements de 7 m et 14 m que pour 28 m, et plutôt durant les mois d'hiver que ceux d'été. La subirrigation a été utilisée, pendant l'été, sur de courtes périodes, mais en l'absence de mesures, aucune données n'a été entrée dans le modèle.

Par ailleurs, le niveau de la nappe prédit pour les écartement de drains de 28 m est assez profond pour permettre les opérations agronomiques en automne et printemps, mais pour des périodes plus courtes qu'avec les écartements de 7 m et 14 m.

Le niveau de la nappe, pour les drains à 7 m et 14 m d'espacement, est très comparable. A 28 m, il est plus élevé de l'ordre de 10 à 20 cm. Sans drainage, le niveau de la nappe a été aussi élevé au printemps, en été et en automne. Concernant le débit des drains, les résultats d'une année ont montré que la différence entre les drains espacés de respectivement 7, 14 et 28 m n'est pas significative. Les crues les plus brèves sont observée sur les écartements les plus faibles. Les débits maximaux observés correspondent également aux écartements qui conduisent au nombre maximum de jours disponibles.

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INTRODUCTION

Drainage is needed in humid regions to provide trafficable conditions for seedbed preparation and planting in the spring, to insure a suitable environment for plant growth during the growing season, and to provide trafficable conditions for harvest operations in the autumn. Computer simulation models can be used to design and evaluate drainage and water table control systems. A computer simulation model called DRAINMOD, which was developed at North Carolina state university (Skaggs, 1978 and 1980) was used to characterize the response of the soil water regime to the water management of a silty alluvial soil in northern Germany under different drainage intensity and to predict the response of the water table and soil water above the water table to rainfall, evapotranspiration (ET), given degress of surface and subsurface drainage. Water table elevations predicted by DRAINMOD are compared to measured values to demonstrate the use of DRAINMOD for analyzing conventional drainage systems.

FIELD SITE / FIELD EXPERIMENTS

Since 1983 fields trials were laid out at Elbe river coastal region of northern Federal Republic Germany. The investigated site " Kehdingen" lie about 2,0 m above the main sea level. The soil is brackisch alluvial clay silt to silty clay. The site is used for arable cropping since 1976.

North Germany belongs to the humid maritime climate zone of Europa. Table 1 shows the main climate datas for Kehdingen region.

Mean or Sum	Air temp °c	Rainfall mm	Evapotranspiration mm	discharge mm
year	8-9	750-800	500-550	200-300
Non.- Apr.	3-4	300-350	100-150	100-300
May - Oct.	14-15	450	400	< 100
Jan.	0-1	63		
July	17-18	96		

Table 1. Mean data of climate for Kehdingen region

The annual rainfall ranges between 750 and 800 mm, while the evapotranspiration ranges between 500 and 550 mm. Perennial winds from west and southwest cause a maritime climate with mild winter and relatively cool summer. In the investigated site no surface irrigation was used.

The pipe drains spaces are 7 m, 14 m and 28 m respectively with average depth of 1 m. The drains empty into an outlet ditch 1,6 m deep. Daily rainfalls, temperatures and air humidities were obtained from weather station ten kilometer away and the potential ET calculated by Haude method (Haude, 1955). Daily values were used as inputs to test DRAINMOD.

The water table elevation midway between drains was measured in 15 cm diamter observation wells, drilled to 3 m and fitted with 30 days rotation time, water level recorders to give a continuous record of the water table amplitute. The saturated hydraulic conductivity was measured in the field using the auger hole method according to Hooghoudt-Ernst (Beers, 1970) and in the laboratory using an undisturbed core method (Hartge, 1966). The infiltration measurements were determined at the soil surface with infiltrometer method (Schaffer and Collins, 1966).

RESULTS AND DISCUSSION

The saturated hydraulic conductivity values (k) varied with initial water table depth and from point to point in the field so geometrical average values were used for the simulations in this study (Table 2).

The k-values decrease with increasing soil depth. In drain depth (1,0 m) has the soil a moderate hydraulic conductivity.

profile depth (cm)	hydraulic conductivity (cm/d)
0 - 60	37
60 - 120	25
120 - 150	14
150 - 200	6

Table 2. Average k values of profile layers

Most of the uses contemplated for the model are related in some way to water table depth and its variation over time. Therefore the model has been tested by comparing measured and predicted water table depths for two years 1987 and 1988 as for example.The measured and predicted daily water table elevations for the 7 m, 14 m, and 28 m drain spacing are given in Figures 1, 2 and 3 during 1987, and in Figures 4, 5 and 6 during 1988.

The total rainfall during 1987 was 890 mm, and the evapotranspiration was 360 mm. The agreement between predicted and measured water table elevations is good particularly for the 7 m and 14 m drain spacing. The observed water table from middle July on (day 190, Figures 1-3) continued to recede, mostly due to high ET, and did not reverse its downward trend until more than one month later when higher rainfall and lower ET accurred. This was not the case for the predicted water table which responded quickly to the raised water table in the drainage outlet due to subirrigation.

The total rainfall during 1988 was 920 mm, and evapotranspiration was 560 mm, The agreement between predicted and measured water table elevations is better during the winter months than for summer months 1988 (Figures 4-6). Subirrigation was used for short periods in summer 1988 by raising the water level in the drainage outlet. But the water level in the outlet was not measured continuously as a result it was not possible to input the subirrigation data in the model or to plott the outlet water levels. During 1987 and 1988 is the agreement between predicted and measured water table elevations better for 7 m and 14 m drain spacing than for 28 m spacing. The optimum drain spacing was determined to be 13-20 m.

The drain depth was 1,0 m so the water table was actually below the drain at 7 m and 14 m drain spacing for a large part of the year. The rate that the water table was drawn down by ET was more rapid than observed particularly for the 28 m drain spacing.

Under ditch drainage (200 m) without pipe drainage remain the water table frequently higher than 70 cm and in winter months reach to the soil surface.

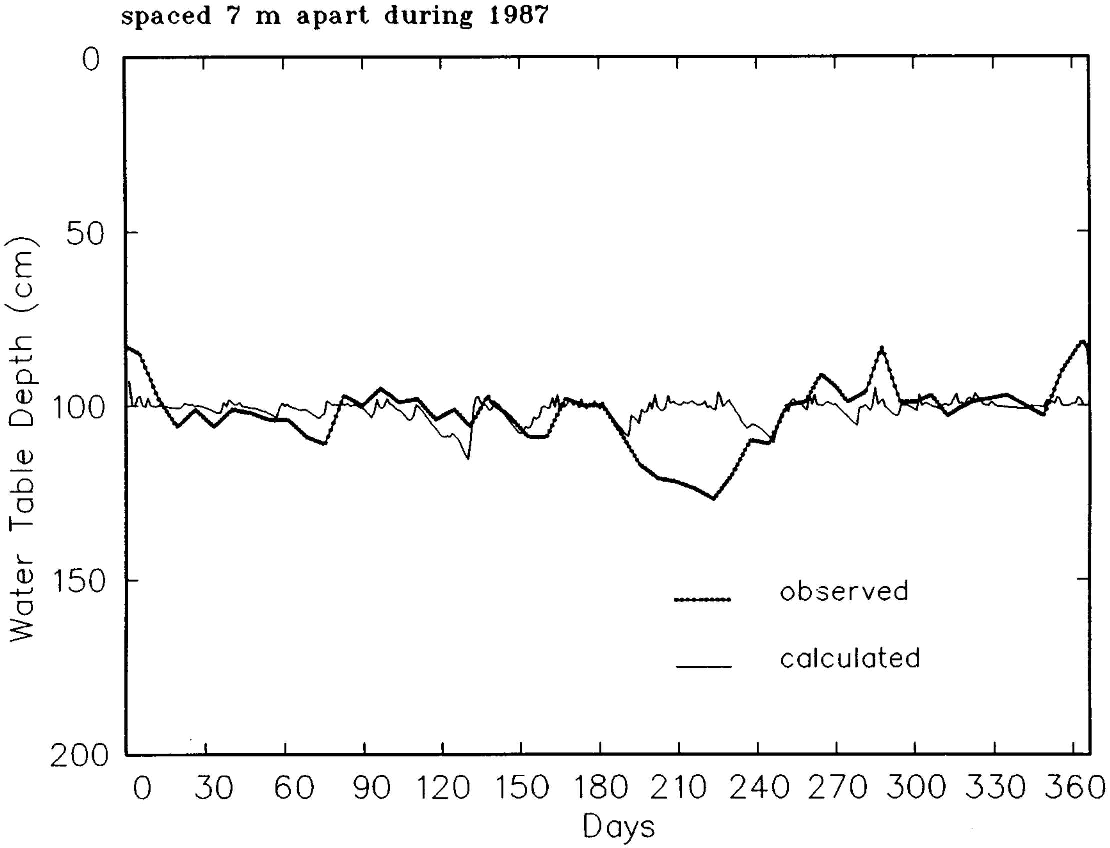

Figure 1. Observed and predicted water table elevations midway between drains spaced 7 m apart during 1987

spaced 14 m apart during 1987

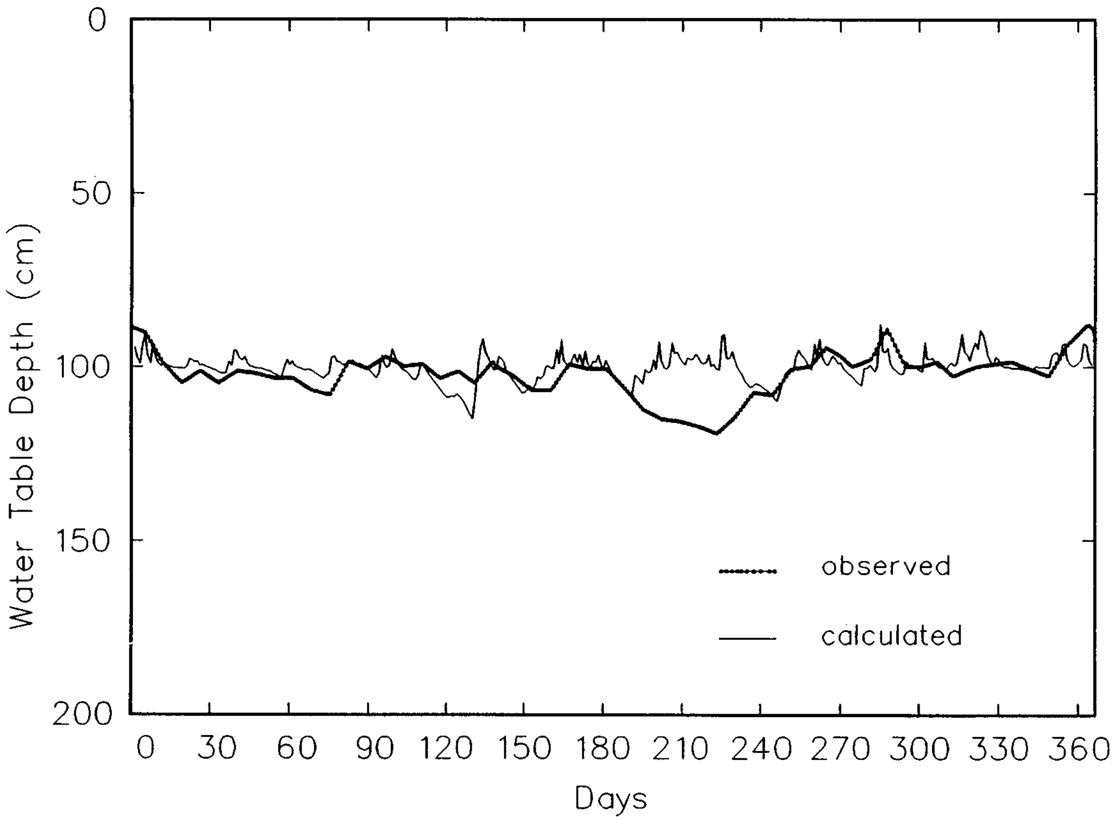

Figure 2. Observed and predicted water table elevations midway between drains spaced 14 m apart during 1987

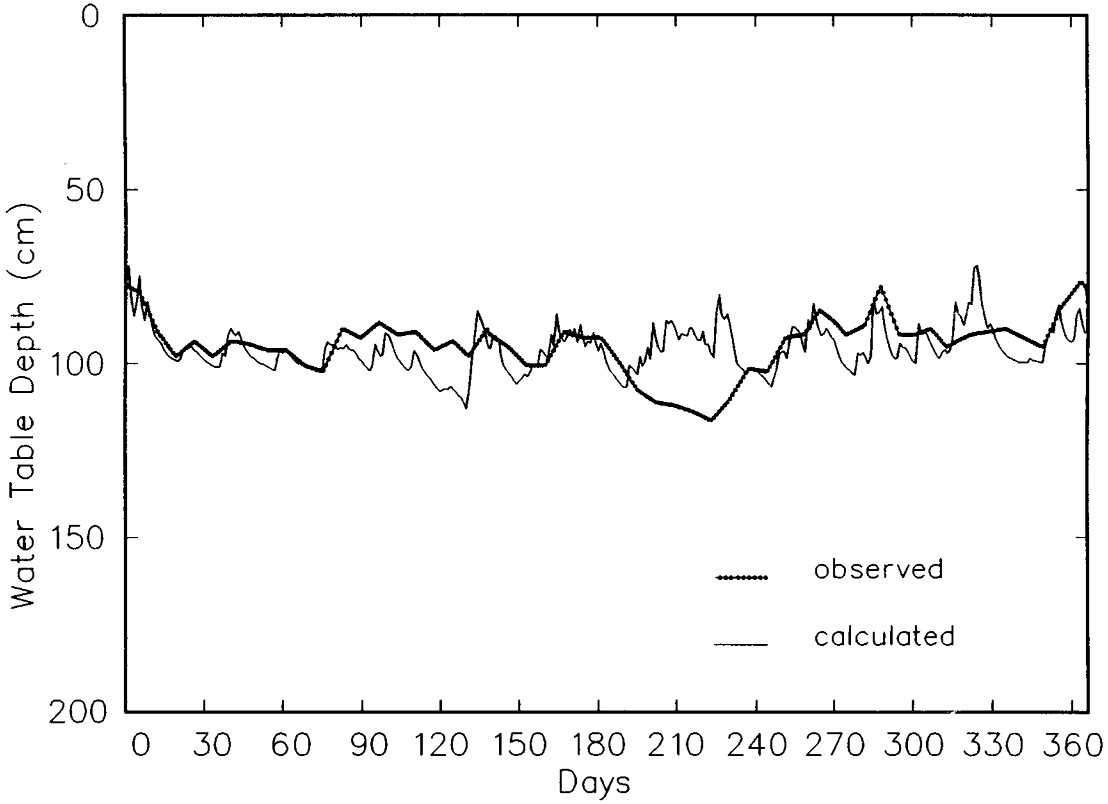

Figure 3. Observed and predicted water table elevations midway between drains spaced 28 m apart during 1987

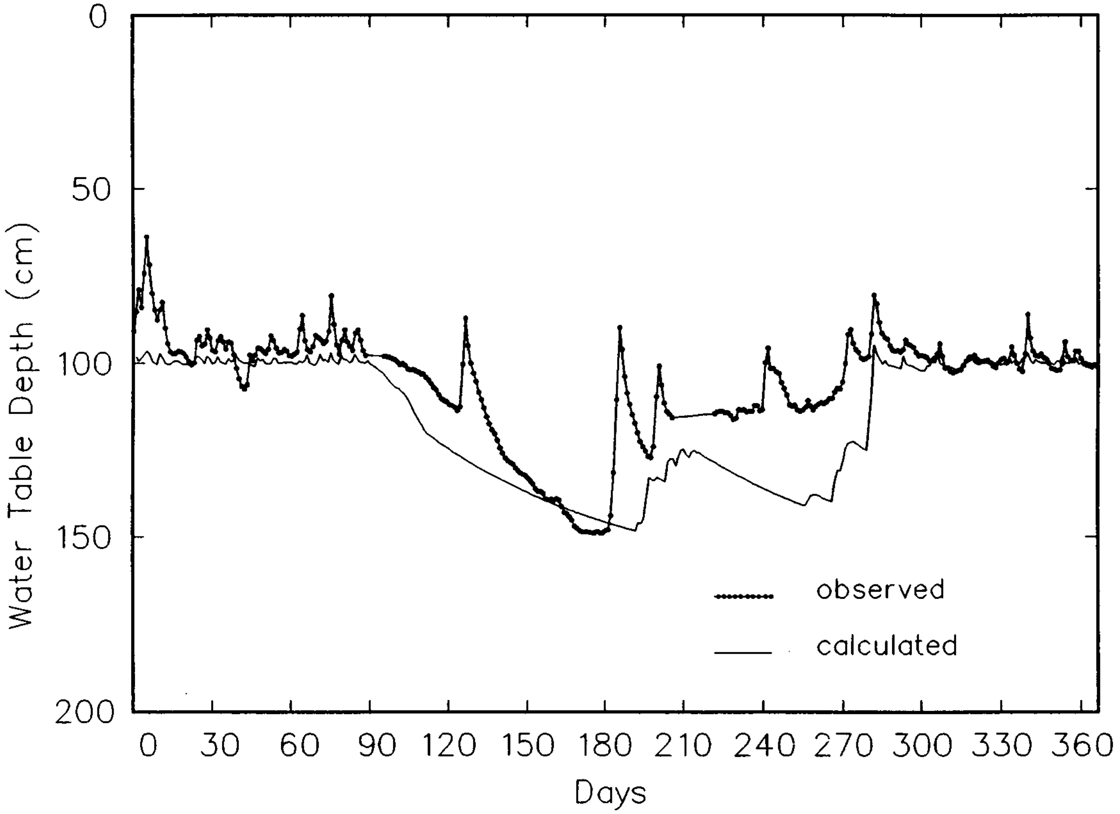

Figure 4. Observed and predicted water table elevations midway between drains spaced 7 m apart during 1988

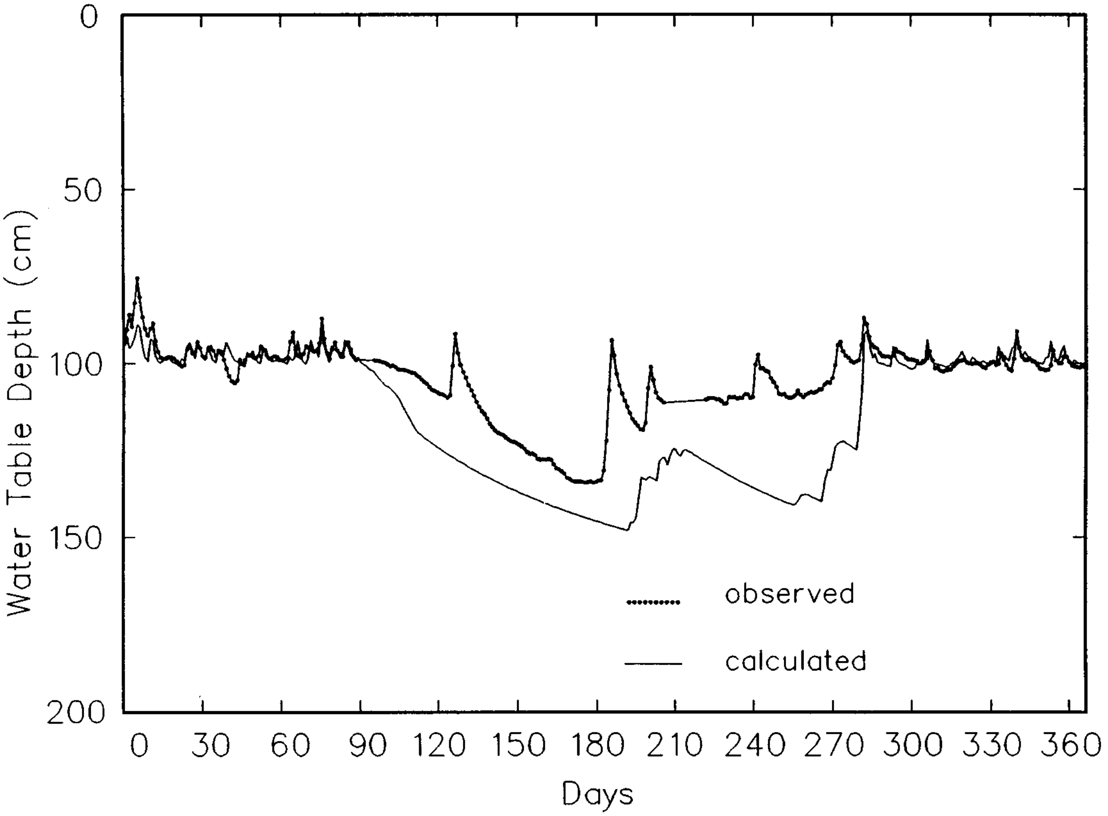

Figure 5. Observed and predicted water table elevations midway between drains spaced 14 m apart during 1988

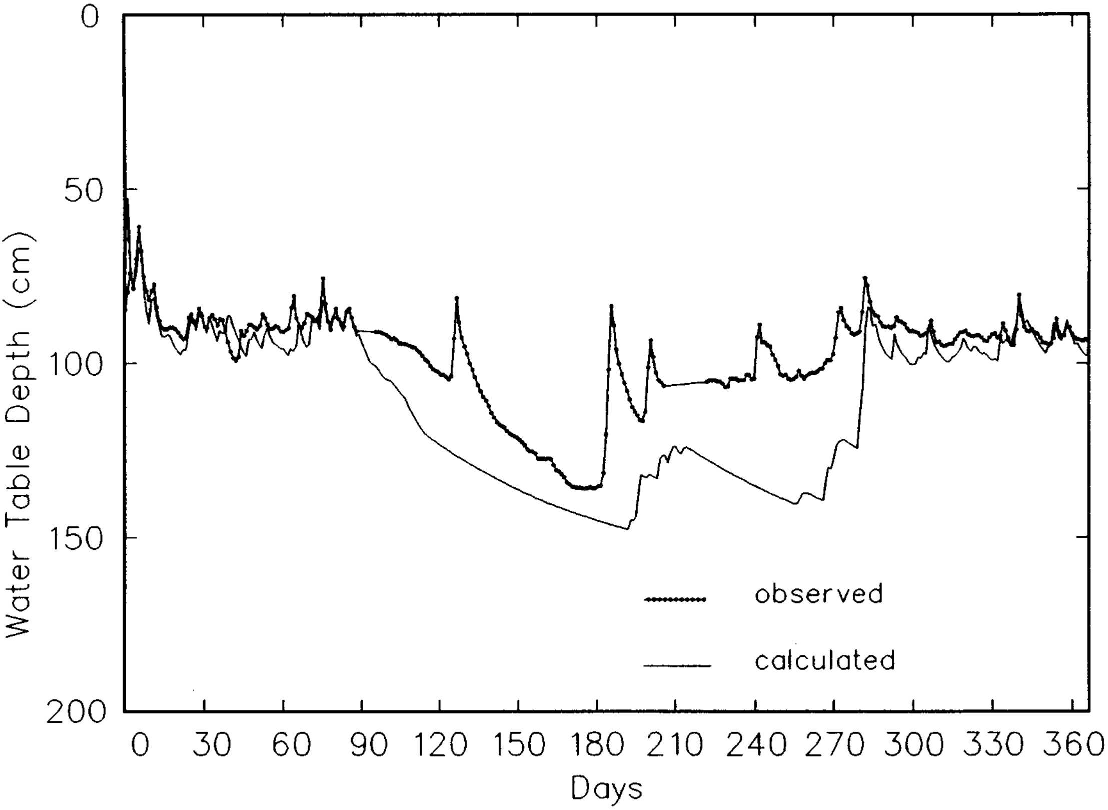

Figure 6. Observed and predicted water table elevations midway between drains spaced 28 m apart during 1988

Trials with a range of values of hydraulic conductivity showed that, agreement could be improved by chaning k. However the results given in Figures 1 to 6 which were obtained with independently measured k values, are considered.

The comparison between predicted drain discharge of drain distances 7 m , 14 m, 28 m and 200 m (ditch drainage) show that there were no significant differences on the annual drain discharge sum between the different drain distances. But the closer the drain distance the shorter the discharge periods and the higher the daily rate of discharge, and as consequence the more the available field working days.

The observed drain discharge in the field is less than the predicted drain discharge because of the drainage effect of the ditches.

The DRAINMOD can be used in the humid regions northern Germany with an accepted manner to simulate or predict water table elevations and soil water conditions, especially when no foreign water exit or no subirrigation use. According to the model the need of pipe drainage was high, without subsurface drainage no suffice trafficable conditions for arable utilization was obtained. Also under the 28 m drain distance , in the investigated site, a drainage success was expected.

The potential for using the DRAINMOD for irrigated soils in arid and semi-arid regions was examind in Egypt (Abdel-Dayem and Skaggs, 1990). The model allows the long term prediction of the effect of irrigation and drainage on salinity in the root zone, crop yield and salinity of drainage water. The development of the submodel for irrigated agriculture requires consideration of the different irrigation practices, irrigation water salinity and crop rotation.

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PARAMETER SENSITIVITY AND FIELD EVALUATION OF SIDRA MODEL

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ABSTRACT. The simulation model SIDRA is based on a semi-analytical and semi-numerical solution to the Boussinesq equation. It has been developed on the ground on theoretical and field experimental results with the aim of a good prediction of drainage peak flow rates. Theoretical aspects and basic equations of the model are presented for the most general case where both soil physical properties and water table shapes are depth-dependant. The parameter sensitivity and field performances of the model are estimated in shallow loamy soils facing a seasonal waterlogging during winter season in France. Water table shape factors are the most sensitive parameters. Drainable porosity is slightly more sensitive for drain flow rate prediction ; hydraulic conductivity is slightly more sensitive for water table elevation prediction. A comparison of experimental and simulated long terme discharge and water table exceedance duration curves shows that the model could be a useful tool to assess the performances and control the relevance of a given subsurface drainage design.

RESUME. *Le modèle de simulation SIDRA est basé sur une résolution semi-analytique et semi-numérique de l'équation de Boussinesq. Il a été développé à partir d'une approche théorique et de l'analyse de résultats d'expérimentations de terrain avec pour principal objectif d'atteindre une bonne prédiction des débits de pointe. Les principales équations du modèles sont présentées dans leur forme la plus générale qui permet de prendre en compte des propriétés hydrodynamiques et des formes de nappe dépendantes de la profondeur. L'étude de sensibilité aux paramètres et l'évaluation des performances du modèle sont réalisées dans le cas de sols limoneux peu profonds, sur la période hivernale où se manifeste l'engorgement des sols en France. Le modèle est très sensible aux variations des facteurs de forme de nappe. Concernant les paramètres hydrodynamiques, les débits simulés sont plus sensibles aux variations de la porosité de drainage qu'à celles de la conductivité hydraulique. A l'inverse les hauteurs de nappe simulées sont plus sensibles aux variations de conductivité hydraulique. Une comparaison sur une longue période des fréquences de dépassement de débits et hauteurs de nappe, simulés et observés, montre que le modèle peut constituer un bon outil de contrôle de l'efficacité d'un réseau de drainage et de son dimensionnement.*

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INTRODUCTION

SIDRA model generates hourly sequences of water table elevations and drainflow rates. The model was developpped on the ground of theoretical and experimental results (Boussinesq 1904, Guyon 1964 and 1980, Lesaffre and Zimmer 1987). Its major objective was to satisfactorily explain and predict high peak flow rates observed in french low permeable shallow loamy soils, which generally occur during and a few hours after rainfall events.

This paper presents the assumptions and the basic principles of the model. It discusses some of the basic assumptions that are used to derive its equations on the ground of experimental results. The sensitivity of the model parameters is presented and the model efficiency to predict long term discharges and water table elevations exceedance duration curves used in drainage design is discussed.

MODEL DESCRIPTION

SIDRA (SImulation of DRAinage) model is based on a semi-analytical and semi-numerical resolution of Boussinesq's equation describing the drainage problem shown in figure 1. The model uses hydrometeorological data (rainfall and potential evapotranspiration) as input data and provides hourly midpoint water table levels and drainflow rates as output data. Depth dependant soil properties are taken into account by the model.

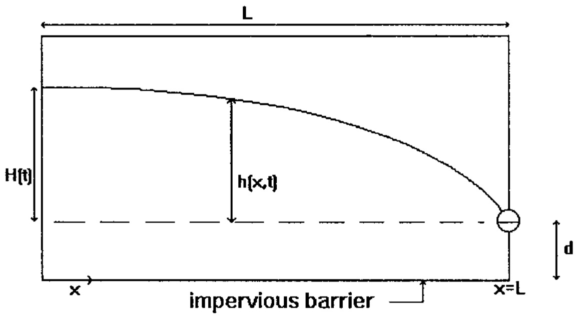

Figure 1. System definition - H(t), water table elevation mid-point between drains, h(x,t), water table elevation at abscissa x, L, drain mid-spacing, d depth to impervious layer

Basic assumptions

The model is based on the following assumptions :

- the aquifer is unconfined and lies on an horizontal impervious barrier;
- the flow transfer above the water table is ignored, but its contribution to the drainflow rate is taken into account by use of the drainable porosity, defined as the volume of water per unit area that is released or stored as the water table moves by a unit distance;
- the total water potential remains constant above drain level inside the water table mid-point between drains; this corresponds to Dupuit-Forchheimer assumption;
- below drain level, flow convergence near the drain pipe is taken into account using Hooghoudt's equivalent depth theory.

Deriving equations

1. *equation of motion*

The horizontal flux q(x) in the saturated zone at any abscissa x is based on the Darcy's law. Combining this law and the use of a *discharge potential function* (F) leads to the equation of motion :

$$q(x,t) = -\frac{\partial F(x,t)}{\partial x} \qquad (1)$$

where

$$F(x,t) = \int_{-d_e}^{h} K(z)\,(\varphi - z)\,dz, \text{ the} \qquad (2)$$

h : water table elevation above drain level at abscissa x and time t;
$K(h)$: depth-dependant saturated conductivity;
d_e : Hooghoudt's equivalent depth;
φ : total water potential.

If Dupuit-Forchheimer assumption is valid, $\varphi(x,t) = h(x,t)$,.where h(x,t) is the water table elevation above drain level at abscissa x and time t. Eq. (2) can be written in that case

$$F(x,t) = \int_{-d_e}^{h} K(z)\,(h - z)\,dz \qquad (3)$$

Eq. (1) shows that $\Delta F(x,t)$, defined as $F(x,t) - F(L,t)$, provides a good assessment of the performance of the system between x and L. We assume here that the drains are not surcharged, even during the recharge stage, $h(L,t) = 0$. After integration by parts and rearrangement of terms, $\Delta F(x,t)$ yields :

$$F(x,t) - F(L,t) = \Delta F(x,t) = \int_0^h K(z)(h-z)dz + h \int_{-d_e}^0 K(z)dz \tag{4}$$

which can be rewritten

$$\Delta F(x,t) = K_{eq}(h)\frac{h^2}{2} + K_2\, d_e\, h \tag{5}$$

with

$$K_{eq}(h) = \frac{2}{h^2}\int_0^h K(z)(h-z)dz \tag{6}$$

$K_{eq}(h)$ is the depth-dependant equivalent horizontal hydraulic conductivity introduced by Wolzack (1978)

and

$$K_2 = \frac{1}{d_e}\int_{-d_e}^0 K(z)dz \tag{7}$$

K_2 is the mean saturated conductivity of the soil horizons located below drain level.

Dividing Eq.(15) by $L^2/2$ yields :

$$J(H) = 2\frac{\Delta F(0,t)}{L^2} = \frac{K_{eq}(H)H^2 + 2K_2 d_e H}{L^2} \tag{8}$$

where

L : drain mid-spacing;
H(t) : water table elevation mid-point between drains

In steady state, this equation is the Hooghoudt's formula with J(H) being replaced by the rainfall intensity.

2. *equation of continuity*

The continuity equation for saturated flow can be written

$$-f(h)\frac{\partial h(x,t)}{\partial t} + R(t) = \frac{\partial q(x,t)}{\partial x} \tag{9}$$

where

f(h) : depth-dependant drainable porosity;
R(t) : net recharge.

3. *solution methods*

The combination of both equations of motion and of continuity as written in Eq. (9) has been solved numerically by Skaggs (1975). It is solved here analytically according to space by use of water table shape considerations. Lesaffre and Zimmer (1987) consider a constant water table shape as defined by Boussinesq. Following Lesaffre (1988), the water table shape will be considered here to be depth-dependant according to the equation :

$$h(x,t) = H(t)\,W(X,H) \qquad (10)$$

where

X : non dimensional abscissa ($X = x/L$) ;
W(X,H) : non dimensional water table elevation at abscissa X ;

Combining Eq. (9) and Eq. (10) yields

$$-f(h)\frac{dH}{dt}\left(W + H\frac{\partial W}{\partial H}\right) + R(t) = \frac{\partial q(x,t)}{\partial x} \qquad (11)$$

The solution involves a double integration of Eq. (11) between 0 and x and, in a second step, between 0 and L. The first integration yields for x=L :

$$Q(t) = \frac{q(L,t)}{L} = R(t) - B(H)f(H)\frac{dH}{dt} \qquad (12)$$

where Q(t) is the drainflow rate per unit area

The second integration combined with Eq. (5) written for x=L yields :

$$J(H) = R(t) - f(H)\,C(H)\frac{dH}{dt} \qquad (13)$$

B and C are called respectively the *first and second water table shape factor* (Guyon 1980, Lesaffre 1988) and are defined as :

$$B(H) = \int_0^1 \left(W + H\frac{\partial W}{\partial H}\right)dX \qquad (14)$$

$$C(H) = 2\int_0^1 \frac{f(h)}{f(H)}(1-X)\left(W + H\frac{\partial W}{\partial H}\right)dX \qquad (15)$$

In the general case, these water table shape factors are depth-dependant. In case of a constant water table shape and of homogeneous drainable porosity, which corresponds to the original Boussinesq assumption (Boussinesq 1904), B represents the area under the curve W(X), between X=0 and X=1. A *third water table shape factor* A(H) can be defined:

$$A(H) = \frac{B(H)}{C(H)} \tag{16}$$

Combining Eq. (12), Eq. (13) and Eq. (16), yields the following equation valid for positive or nil net recharge (Lesaffre 1988):

$$\mathbf{Q(t) = A(H)\ J(H) + (1-A(H))\ R(t)} \tag{17}$$

Eq. (17) is a more general form of the equation introduced by Lesaffre and Zimmer (1988) for the case of constant watertable shapes. This equation shows that during recharge stage drainflow rates are generated, firstly, by the water table drawdown and secondly by a *direct* contribution of the net recharge. The water table shape factor A ranges between 0.8 and 0.9 which means that this contribution is about 10 to 20 percent of the total net recharge. This equation allows a satisfactory prediction of drainage peakflows in drained lands and perhaps also in hydraulic systems with a shallow water table.

As for the case of negative net recharge (i.e., the evapotranspiration rate is higher than the rainfall rate), water is assumed to be stored or depleted from a reservoir located in the upper part of the unsaturated zone when the water table recedes below a critical water table elevation. Above this critical elevation the net recharge is entirely pumped from the water table according to the following equations:

$$Q(t) = A\ J(H) \tag{18}$$

$$-\ B\ f(H)\frac{dH}{dt} = R(t) - A\ J(H) \tag{19}$$

Programm description

A simplified flow chart of SIDRA model is presented in Fig. 2. SIDRA model uses climatic data (rainfall, Et) and soil characteristics and generates sequences of mid-point water table elevations and drainflow rates at an hourly time step.

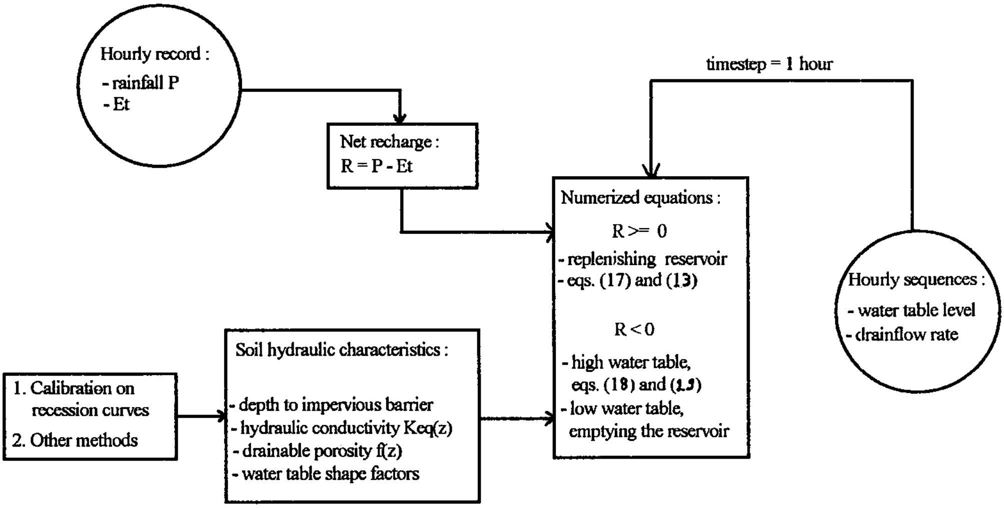

Figure 2. Simplified flow chart of SIDRA

1. *calculation of the net recharge*

Hourly net recharge values are calculated using the following procedure. Daily Et values provided in France by the Meteorological Office (Choisnel 1985) are transformed into hourly data, under the assumption that the evapotranspiration varies as a sine function between early morning and late afternoon. Et is zero during the night. Under french conditions where drainage mainly operates in winter the actual evapotranspiration is assumed to be equal to potential evapotranspiration. The hourly Et values are substracted from hourly rainfall data that ought to be recorded in the vicinity of the site under study.

2. *system and soils characteristics*

Soil profile is described by the hydropedologic data, hydraulic conductivity and drainable porosity, and the water table shape factors A and B. For hydropedologic data, three cases can be considered : (1) profile being divided in layers with homogeneous properties, (2) profile being defined with local properties or (3) hydrodynamic data being power functions of the elevation except for the plow layer assumed to be homogeneous. In each case, the model generates a profile of the soil parameters K_2, $K_{eq}(H)$ and f(H). The water table shape factors can be either constant or depth-dependant. Depth-dependant water table shape factors are determined by use of the following procedure :(1) for the steady state, calculation of the W(H) function at several abscissa between drain and mid-drain location, (2) derivation of W(H) function following H, and (3) numerical integration of the functions B(H) and C(H) using Eq. (14) and (15).

The depth-dependant equivalent hydraulic conductivity $K_{eq}(H)$, drainable porosity $f(H)$ and water table shape factors, $A(H)$ and $B(H)$ are the elaborated parameters of the model.

The system considered can be either burried pipes or open ditches or channels. It is characterized by a spacing and a depth.

3. *parameter determination*

Parameters of the model can be either :

- measured in situ : field effective and depth-dependant values of hydraulic conductivity and drainable porosity are however seldom available ; the most accurate measurement method seems to be the Guyon's pumping test (Dorsey et al 1990, Lesaffre 1990);

- calibrated on a single recession curve : in that case, provided that neither Et nor deep seepage interact with the watertable drawdown, Eq. (13) can be integrated in case the soil is homogeneous or if the soil properties are power functions of the elevation.

  When the drains lie on the impervious layer, SIDRA provides an exact solution of Eq. (13) using an iterative process to calculate depth-dependant parameters from drainflow and drawdown rates using the following procedure:

  - the calibration starts with theoretical water table shapes B and C corresponding to the Boussinesq assumption;

  - in a first step, the hydropedological parameters $K_{eq}(H)$ and $f(H)$ are identified by inverse resolution of equations (12) and (13);

  - in a second step, if changes of the water table are taken into account, new water table shape factors are calculated; otherwise the calculation is terminated;

  - the calculation is resumed at the first step untill a maximum of 10 iterations is reached or until the changes of the parameters are below a threshhold.

- calibrated on drainflow rates and water table elevation sequences by an inverse method.

4. *simulation*

During the selected period, hourly water table elevations and drainflow rates are simulated by integration of the time-dependent, non linear, first order differential Eq. (13) or Eq. (18) then Eq. (12). These differential equations are numerized by a fourth order Runge Kutta method.

The net recharges either contribute to the water table movement or to the changes of water content of the surface reservoir as previously described. Recharge of the water table only occurs when that surface reservoir has reached its full capacity. The sequence of water contents of the surface reservoir is also an output of the model.

MODEL VALIDATION AND SENSITIVITY OF THE PARAMETERS

Field details

The model performances and the sensitivity of the parameters were checked in Arrou's field experiment located in the south-west of Paris. The soil is an albaqualf developed on a plateau loam. Its properties are presented in table 1 and are representative of many loamy fairly low permeable soils found in France. The drains rest on the impervious layer at a depth of 0.80 m and drain spacing is 10 m. The field experiment is equipped with V-notch weirs associated with an ultrasonic head-level recording gage and a tipping-bucket rainfall recorder. Water table elevations are measured in tube wells with the same ultrasonic sensor at an hourly time step.

The climate conditions prevailing in France result in seasonal waterlogging in low permeable soils. A perched water table resting on the impervious barrier is present during a few winter and early spring months called the "intense drainage season" (Lesaffre and Morel, 1986).

Plough layer	- thickness	0.23 m
	- hydraulic conductivity	2 m/d
	- drainable porosity	3%
Subsoil	- thickness	0.52
	- equivalent hydraulic conductivity at the top (heterogeneity coefficient)	0.41 m.d 0.74
	- drainable porosity at the top (heterogeneity coefficient)	0.026 0.37

Table 1. Soil properties of Arrou's field experiment

Hydraulic characteritics of the soil were calibrated rather precisely by analysis of recession curves. These hydraulic characteristics were assumed to be power functions of the elevation above the impervious layer, the power of the hydraulic conductivity being twice the one of the drainable porosity. Theoretical considerations (Guyon 1980) show that the water table shape is elliptical and constant in that case.

Sensitivity of the parameters

The sensitivity of SIDRA's parameters was first estimated on a simple version of the model where the hydraulic characteristics were taken as power functions of the elevation above drain level, even in the plow layer (Favier, 1989). The number of parameters amounts in that case to 6. The sensitivity of the parameters is checked for drainflow rates by plotting the variations of the model efficiency versus the relative variations of the model parameters around the nominal values presented in table 1. The model efficiency, assessing whether the agreement between the observed and predicted drainflow rates is acceptable, is calculated by use of the classical function of Nash and Sutcliffe (1970) defined as :

$$e = 1 - \frac{\sum_{i=1}^{N}(Qobs_i - Qsim_i)^2}{\sum_{i=1}^{N}(Qobs_i - \bar{Q}obs)^2} \qquad (20)$$

where $Qobs_i$: measured drainflow rate at time step i
$Qsim_i$: predicted drainflow rate at time step i
$\bar{Q}obs$: average drain flow rate of the sequence

The test was carried out for a two year period. Efficiencies given below and presented in the figures are relative to that period and should not be taken as absolute values; they give nevertheless indications about the relative sensitivity of the parameters.

The classification of the parameters is as follows (figure 3) :

- the water table shape coefficients are the most sensitive parameters; a variation of 10 % of these parameters induces a 10% decrease of the model efficiency;
- the critical water table depth of Et interaction with the water table is not sensitive under the french conditions since evapotranspiration is generally very low during the intense drainage season;

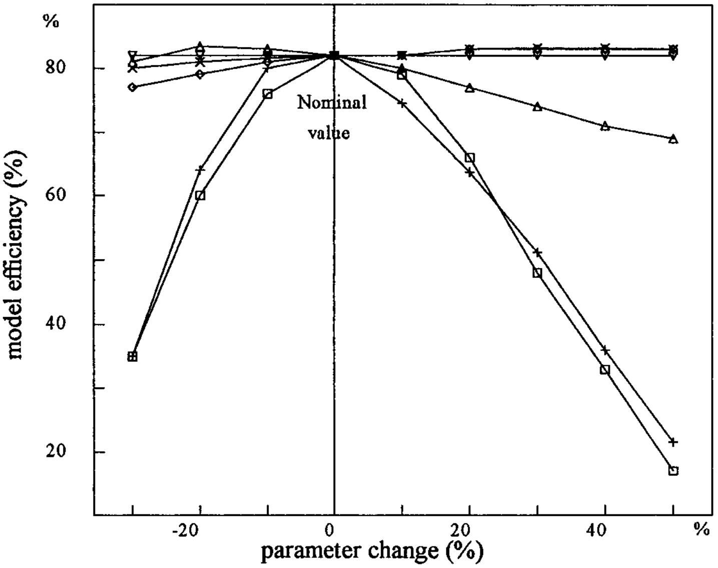

Figure 3. Model efficiency for drainflow rate predictions versus relative changes of the parameters from their nominal values - Data from Arrou's field experiment for 80-81 and 82-83 winter seasons -
□ **B,** + **C,** ◇ **Keq,** △ **f,** × **m,** ▽ **S**

- the soil hydraulic parameters present an intermediate behaviour; a change of 10% to 50% of the parameters induce a 2-3% to 4-10% change of the model efficiency; the sensitivity to the drainable porosity appears to be higher when it is overestimated; the sensitivity to the hydraulic conductivity appears to be higher when it is underestimated;

Complementary investigations were carried out on a more detailed version of the model, distinguishing the plow layer from the subsoil. For drainflow rates simulation, the sensitivity of drainable porosity is slightly higher than that of the hydraulic conductivity (figure 4). On the contrary, the hydraulic conductivity is a more sensitive parameter then drainable porosity for water table elevation prediction (figure 5).

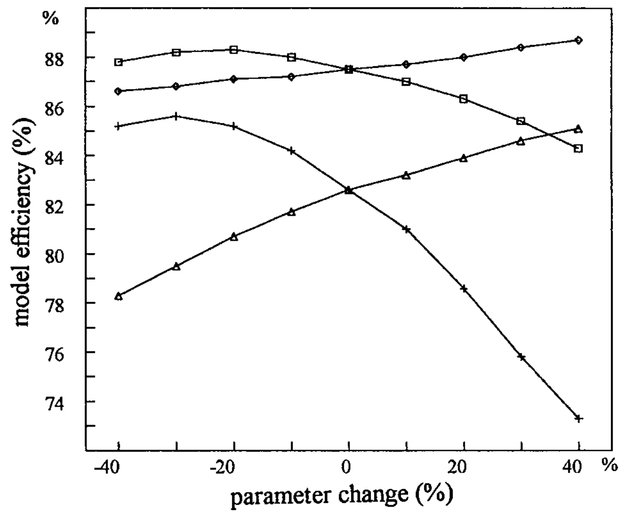

Figure 4. Model efficiency for drainflow rate predictions versus relative changes of drainable porosity and hydraulic conductivity from their nominal values - Data from Arrou's field experiment for 81-82 and 83-84 winter season -

□ **f 81/82,** + **f 83/84,** ◇ **Keq 81/82,** △ **Keq 83/84,**

These results ought to be confirmed for a larger variety of situations of soils and climate. One should also bear in mind that the first objective of the sensibility analysis is to determine which accuracy the measurements of the parameters should aim at for a given objective of quality of the model predictions. Therefore, a relative change of 30% of a parameter value has not the same practical meaning for a parameter which can be measured with a 5% accuracy than one which can only be measured with a 30% accuracy.

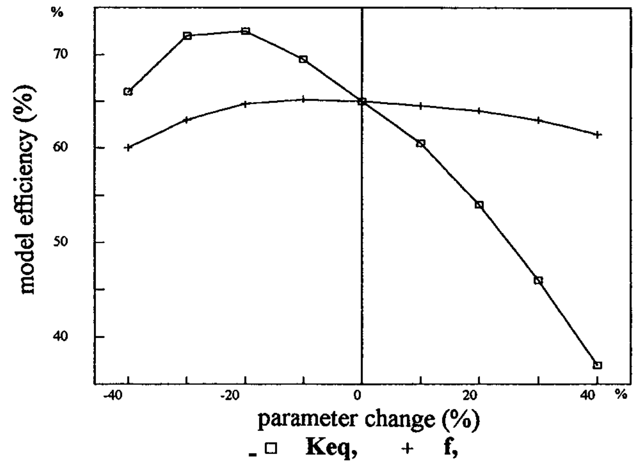

Figure 5. Model efficiency for water table predictions versus relative changes of drainable porosity and hydraulic conductivity from their nominal values - Data from Arrou's field experiment for 81-82 winter season

Quality of model prediction

The quality of the model predictions was discussed by Lesaffre and Zimmer (1988) who compared experimental and predicted sequences as well as exceedance durations of drainflow rates and water table elevations. Fairly good predictions were achieved for two winter seasons. The model simulation is checked here by comparison of measured and simulated exceedance durations of water table elevations and of drainflow rates. During the whole period, the hydraulic characteristics of the soil were assumed to be constant although this assumption is doubtful since a shallow subsoiling occured in 1981.

The annual exceedance durations of drainflow rates ranging between 0.75 and 2.0 l/s/ha were statistically analyzed so as to determine their 2, 5 and 10 years return periods (Fig. 6) following the method presented by Lesaffre (1988). Due to a lack of water table data for a few winter seasons of the 1974-1988 period, the same analysis was carried out for only 2 and 6 year return periods (Fig. 7).

The predicted exceedance durations were overestimated for drainflow rates below 1.5 l/s/ha and slightly underestimated above. For all return periods a very good prediction was achieved for 1.5 l/s/ha (Fig. 6). The 70 percent confidence intervals of the exceedance durations were estimated. These intervals decrease when the drainflow rates increase for predicted as well as for measured values. For instance for a 10 year return period the half-interval decreases from 35 hours to 18 hours for drainflow rates varying between 0.75 and 1.5 l/s/ha. The measured half-interval varies between 26 and 18 hours. The associated coefficient of variation increases for predicted as well as for measured data from 16% to 30%

For the whole range of drainflow rates the discharge exceedance durations do not differ statistically.

Predicted water table exceedance durations are very close to the measured ones especially for high water table elevations. The 70 percent confidence intervals decrease when water table elevations increase. For the six year return period the half-interval decrease from 300 (resp. 190) to 30 (resp. 20) hours for measured and predicted data. The associated coefficients of variation are constant for the whole range of water table elevations; they equal 25% for experimental data and to 15% for predicted ones.

The better prediction for the water table elevations as compared to the drainflow rates results in fact from more variable quality of the annual exceedance duration curves of water table elevations. But the discrepancies between observed and predicted values compensate one another. In the case of drainflow rates the overestimations of the durations below 1.5 l/s/ha and the underestimations above also characterize many of the annual exceedance duration curves: the discrepancy is likely the result of insufficiencies in the description of the mechanisms by the model. Two reasons can be invoked at this stage:

1. surface runoff intercepted by the trench backfill might occur which increases the frequency of high drainflow rates;

2. in the model the recharge of the water table stops as soon as rainfall stops ; in fact the recharge lasts about 10 to 20 hours after the end of the rainstorm which, according to Eq. (17) means that drainflow rates are likely to be underestimated for a few hours after the rainfall event.

CONCLUSIONS

1. During recharge of the water table the drainflow rate is the sum of two terms, one being proportional to the water table elevation according to Hooghoudt equation, the second one being porportional to the recharge rate of the water table. this is demonstrated even for the case where deformation of the water table shape occurs. This property and its associated equation (Eq. (17)) can be useful to determine recharge rates of water tables.

2. Water table shape factors as defined in Eqs. (14) and (15) are the most sensitive parameters of the model. Hydraulic conductivity and drainable porosity are less sensitive but the error associated with their field measurement might be more important. Regarding these hydraulic properties, drain flow rate predictions proved to be more sensitive to hydraulic conductivity ; water table elevations on the contrary proved to be more sensitive to drainable porosity.

3. Exceedance durations of drainflow rates and water table elevations proved to be satisfactorily predicted by the model which could be a useful tool to control the relevance of a drainage design.

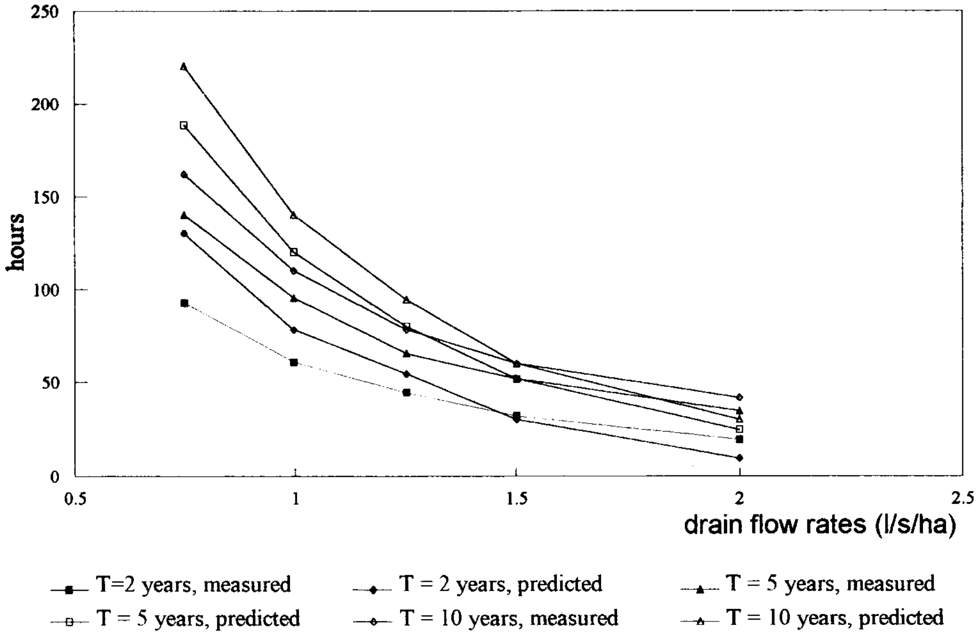

Figure 6. Measured and predicted discharge exceedance durations for 2, 5 and 10 year return periods in Arrou.

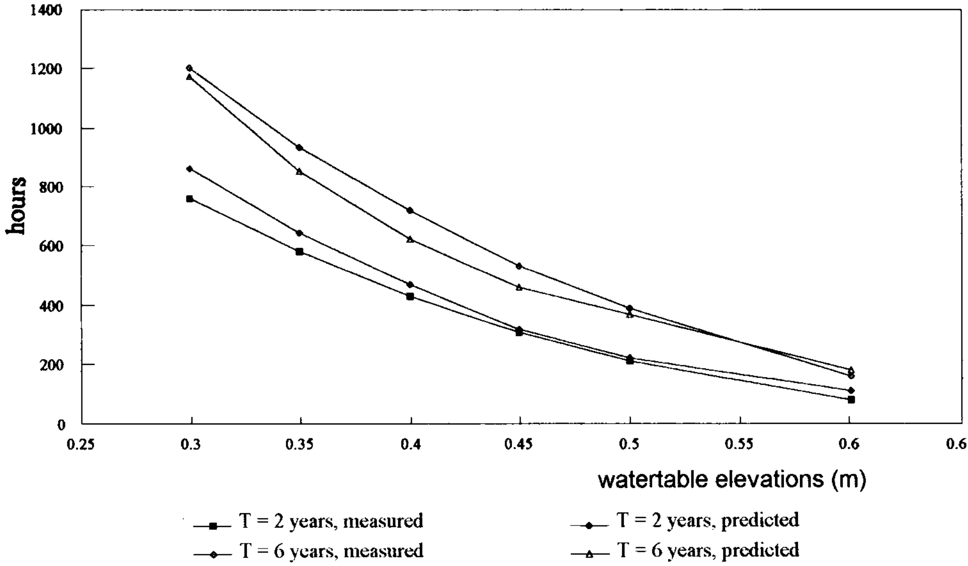

Figure 7. Measured and predicted water table elevation exceedance durations for 2 and 6 year return periods in arrou.

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SIMULATING HYDRAULIC POTENTIAL DISTRIBUTION OF SATURATED UNSATURATED FLOW IN A DRAINED SOIL

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ABSTRACT. DRAINET, a model to simulate saturated-unsaturated flow in drained soils, is used to determine characteristics of water flux as observed in a pipe-drained soil in Northern Germany (Meldorf). The model uses finite differences as a technique to solve the Richards equation. This paper presents only the simulation of hydraulic potentials and drain discharge. The model proves to be very sensitive to soil characteristics, i.e.: soil moisture retention curve and hydraulic conductivity curve. The fitting of these curves was reached by trial and error, based on field observations and laboratory soil tests. The simulation presents hydraulic potential distribution patterns (including matrix - and pressure potentials), which are commonly smoother than the observed values. The agreement between the simulated and observed data (standard deviation approx. 10%) appears to be acceptable for the intended use, that is evaluating the agronomic benefits achieved by field drainage.

RESUME. *Le modèle DRAINET simule les transferts d'eau saturés et non saturés en terrains drainés. Ce modèle, qui résoud l'équation de Richards par la méthode des différences finies a été utilisé pour étudier les flux dans un sol drainé par tuyaux enterrés du Nord de l'Allemagne (Meldorf). Cet article décrit essentiellement la simulation des charges hydrauliques. Le modèle se révèle être très sensible aux courbes caractéristiques : pression et conductivité hydraulique en fonction de la teneur en eau du sol. Ces courbes ont été ajustées par une méthode essai/erreur en comparant les valeurs simulées et mesurées et par des mesures de laboratoire. Les résultats sont présentés sous forme de schémas d'écoulement. Les valeurs simulées sont plus régulières que les valeurs mesurées; elles concordent avec ces dernières de manière satisfaisante (déviation de l'ordre de 10%) eu égard aux utilisations possibles du modèle, notamment pour évaluer l'intérêt agronomique du drainage.*

INTRODUCTION

In order to analyse and interpret the effects of agricultural drainage from an agronomic point of view (trafficability and workability of soils, nutrient transport, yields, etc.), the variations of the hydraulic potentials in time and space within the rooting zone are of interest. Hydraulic potential patterns in subsurface drained soils are the result of the process of water recharge and discharge under certain initial and boundary conditions. These processes are affected by various factors like rainfall intensity, evapotranspiration, soil characteristics, agronomic aspects and drain design like drain spacing, - depth and diameter (Skaggs 1987, Feddes et al. 1988). A drainage model, which takes these factors into account will be applied. Furthermore potential patterns and distributions

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will be shown with observed, as well as with simulated values for a drained agricultural plot in Northern Germany (Meldorf). It is the intention to use this model for quantifying benefits achieved by agricultural drainage.

METHODS USED

The two dimensional model DRAINET links saturated and unsaturated water flow towards a subsurface-drain in a layered soil. It allows the use of different soil characteristics in the trench backfill and in three horizontal soil layers. Richards equation is solved by means of finite differences method, using a rectangular grid, which is not necessarily equidistant. For the results presented in this paper a very crude grid of only 9*11 nodal points was used. This allowed simulations over a period of several months with acceptable computer operation time on a personal computer (Hundertmark 1990, Reinhard 1984). The curve of soil moisture versus matrix potential was approximated using the model proposed by van Keulen (1986),

$$\theta_a = \theta_s \, e^{-\ln(\gamma \Psi^2_M)} \qquad \Psi_M \leq -1\text{cm} \qquad (1)$$

with,

θ_a = actual soil moisture content [cm^3/cm^3]
θ_s = satured soil moisture content [cm^3/cm^3]
Ψ_M = matrix potential [cm]
γ = coefficient [1/cm^2]

The curves of hydraulic conductivity versus matrix potential curves followed the model proposed by Rijtema (v.Keulen et al.1987).

$$K = K_s \, e^{\alpha \Psi_M - \Psi_{Ma})} \qquad \Psi_{Ma} \leq \Psi_M \leq \Psi_{M\,max} \qquad (2)$$

with,

K = unsaturated hydraulic conductivity [cm/day]
K_S = saturated hydraulic conductivity [cm/day]
Ψ_M = matrix potential [cm]
Ψ_{Ma} = matrix potential at air entry point [cm]
α = coefficient [l/day]

The calculation of the drain discharge by DRAINET can be described by the following expression:

$$Q = K_s . \left[\frac{\Psi_{Hz,\,n-1} - \left(Y_{z,\,n} + f\right)}{\Delta X_n - \frac{d}{2}} . \pi \frac{d}{2} + \frac{\Psi_{Hz+1,\,n} - \left(Y_{z,\,n} + \frac{d}{2} + f\right)}{\Delta Y_z + 1 - \frac{d}{2}} . \pi \frac{d}{4} + \frac{\Psi_{Hz-1,\,n} - \left(Y_{z,\,n} - \frac{d}{2} + f\right)}{\Delta Y_z - \frac{d}{2}} . \pi \frac{d}{4} \right] \tag{3}$$

where

Ψ_H = hydraulic potential [cm]
Y = gravitational head [cm]
f = drain entry resistance [cm]

For further details see also figure 1.

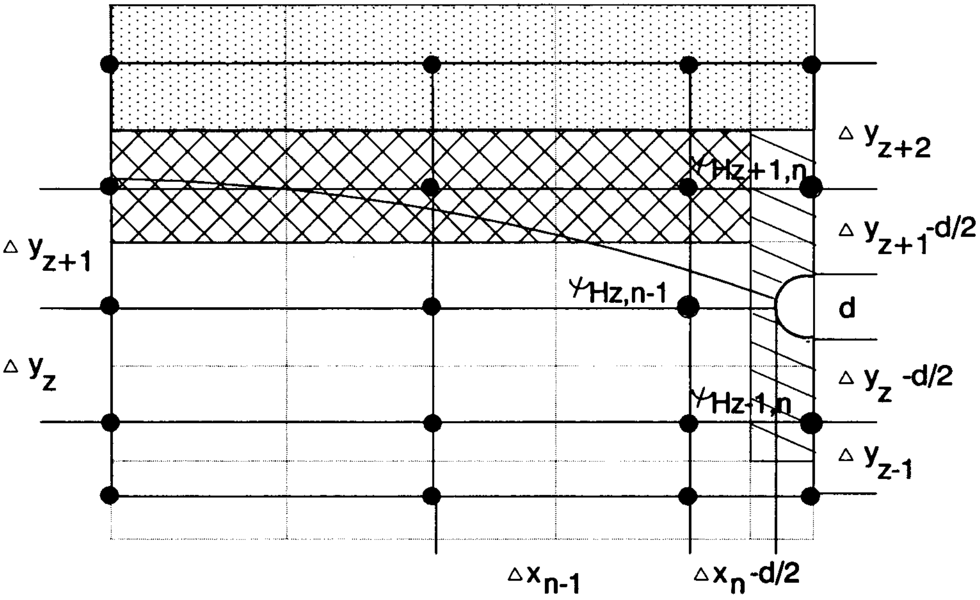

Figure 1. Discretisation of the model in a halfplane perpendicular to the drain.

The model sensitivity against θ-Ψ and K-Ψ functions has been tested. Altering in the θ-Ψ function by 10% resulted in a simulated Ψ_H value, which differed about 7% from the original one. A deviation of 7% is also obtained when the value γ of the θ-Ψ function (see eq 2) is varied for about 10%. The same test has been made with K and α values, which appear in the K-Ψ function. Changing K for 10% the simulated tensions changed for about 2%. The same order of size applies for α changes.

Field data were collected from a soil located in the coastal marshland of Northern Germany (Speicherkoog; Meldorf, Schleswig-Holstein). Its texture can be classified as loamy silt (approx. 35% fine sand, 55% silt and 10% clay) with thin sandy layers (Guenther 1987). Three drains, each with a single outlet, were selected from a subsurface drainage system, spaced 10m apart with an average drain depth of 0.85m. The following data were automatically recorded on an hourly basis: rainfall, potential evapotranspiration, drain discharge, water table in between the drains (Sm distance perpendicular to drain lines) and matrix potentials in 0.1, 0.2, 0.4, 0.6, 0.8 and 1.0 m soil depths and 0.3, 2.5 and 5.0 m apart from the drain line.

CALIBRATING THE MODEL

All data required to run the model (chpt.2) were fitted to field observations by trial and error method, supported by some laboratory soil tests. Fitting was done in a first step with a data set of a selected ten days period in spring 1988 (Fig.2).

It took great effort to bring the observed reactions of the hydraulic potentials in the saturated and the unsaturated zone into correspondence. The results of this fitting of soil characteristics are shown in table 1.

Parameter	Location/Layers			
	Trench	0 - 0.3 m	0.3 - 0.4 m	0.4 - 1.6 m
K_S [cm/day]	15	20	18	13 (5)
α [1/day]	0.08	0.08	0.08	0.05
γ [1/cm^2]	0.0045	0.0035	0.0035	0.0035
θ_S [cm^3/cm^3]	0.52 (0.62)	0.52 (0.54)	0.48 (0.54)	0.50 (0.52)
Ψ_{Ma} [cm]	-10	-10	-10	-10

Table 1. Fitted soil characteristics (measured values in brackets)

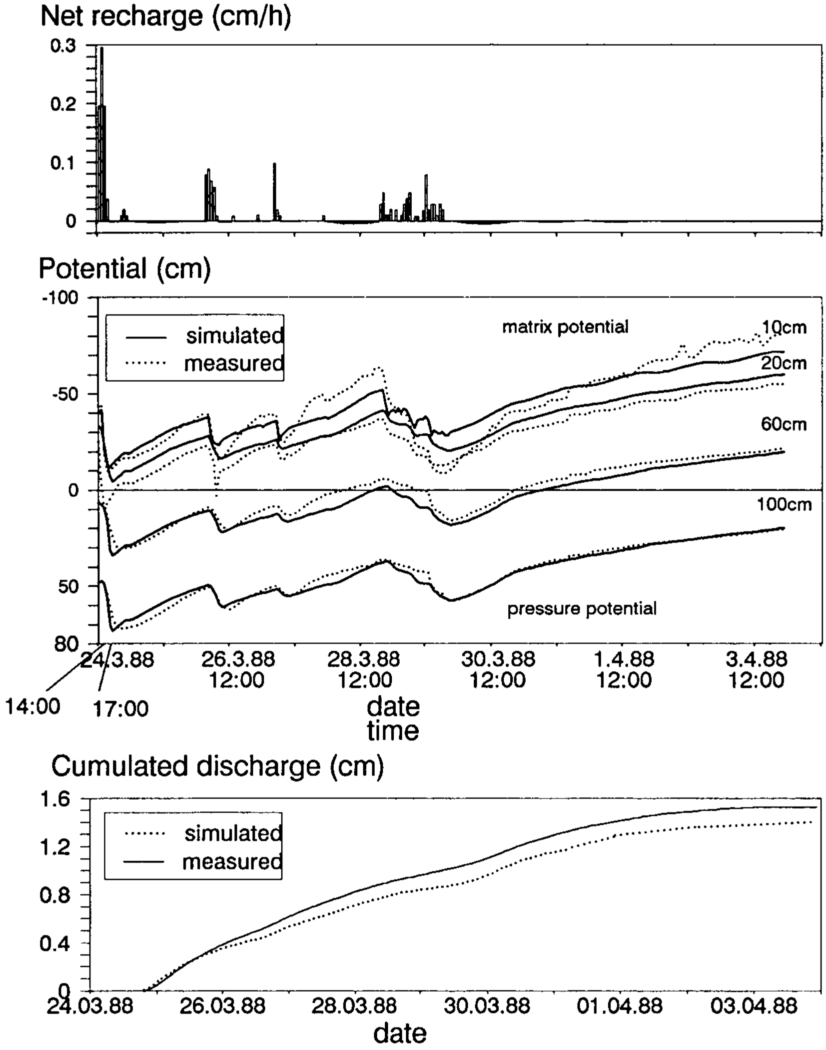

Figure 2. **Net rainfall, observed and simulated matrix potential and acumulated drain discharge during the end of march 1988 at one hour interval at four soil depths, measured midway between drains, Meldorf (FRG).**

RESULTS

Judging the results presented below one has to keep in mind, that they apply to the same period for which the parameters (table 1) have been fitted. Fig.2 gives the observed and simulated tensiometer readings at four soil depths. Deviations do not exceed ten percent and may be considered satisfactory for the purpose explained. The sudden drop of the tensiometer readings on the 26th at 0.2 m depth may be caused by preferential water flow along the tensiometer tube. Once detected, actions were taken to avoid this problem. During the period presented, a situation, which would allow for farm cultivation without adversely affecting soil structure, is never reached according to rules used in Northern-Germany (i.e. matrix potentials in the upper layer are always higher than 100 cm).

The water potential distribution patterns are presented in more detail in Fig.3 and 4 for the situation on the 24th of March. The values are presented in the way proposed and used by Lesaffre and Zimmer (1988) and Zimmer (1988). Fig.3 and Fig.4 show in their lower portions the observed potentials to the left and the simulated potentials to the right. Measurements at equal horizontal distance from the drainage trench are presented in the form of lines which are split into two groups (each consisting of three, respectively four lines):

- the left group shows the vertical distribution of matrix potentials at different distances from the drain pipe, i.e. 0.0 m (the most left line), 0.3 m, 2.5 m and 5.0 m.
- the right group shows the vertical distribution of the hydraulic potentials (matrix/pressure potential plus gravitational potential).

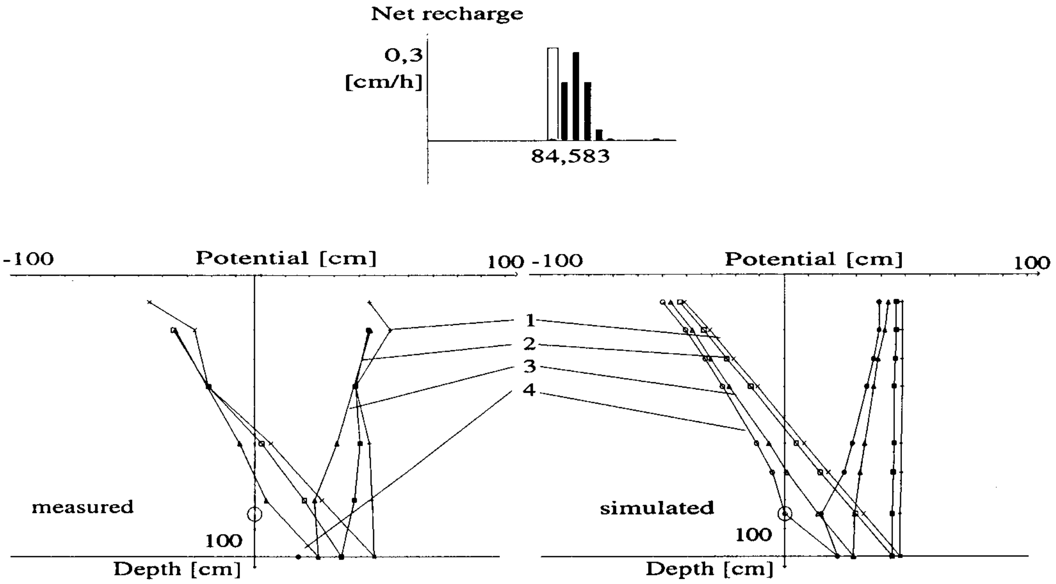

Figure 3. Observed (left side, bottom) and simulated (right side, bottom) potential patterns, just before rainfall on the 24th of March, 1988 Meldorf, at different depths and distances apart the drain line: 0 m = trench (line 4), 0.3 m (line 3), 2.5 m (line 2) and 5.0 m (line 1). On top: hourly rainfall: the open bar shows that there is no rainfall at time 84,583 i.e.2.00 pm but rainfall is expected within the next four hours with an intensity of 0.2, 0.3, 0.2 and 0.05 cm/hour (compare with Fig.2).

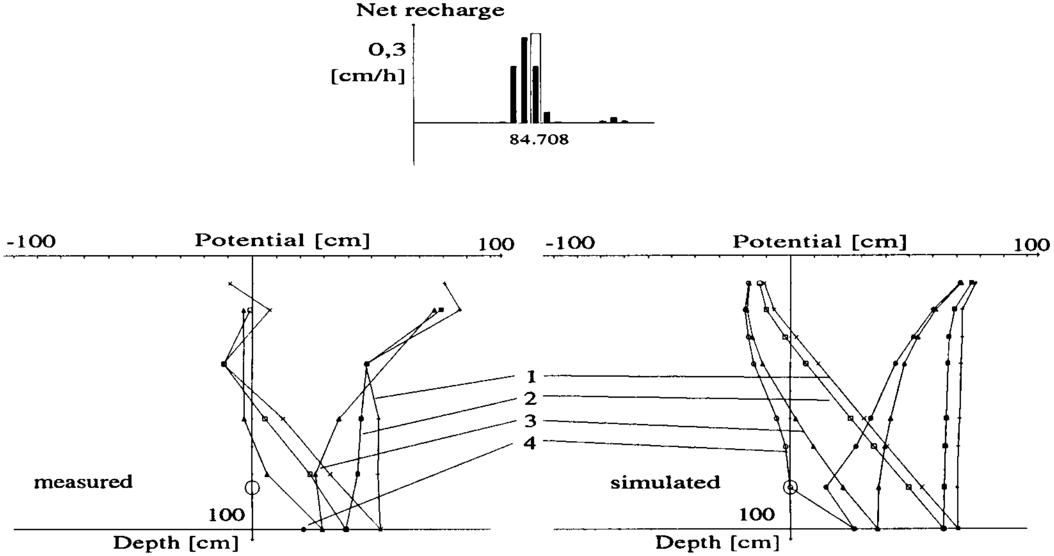

Figure 4. Observed (left side, bottom) and simulated (right side, bottom) potential patterns, after 3 hours of rainfall on 24th of March, 1988, Meldorf. Data are from different depths and different distances apart the drain line: 0.0 m = trench (line 4), 0.3 m (line 3), 2.5 m (line 2) and 5.0 m (line 1). On top-hourly rainfall, actual value in the open bar at time 84.708, i.e. at 5 pm (see also Fig.2).

The matrix potentials (left group) give an indication of water content in the soil, its trafficability and workability, whereas the hydraulic potentials (right group) offer an insight into the soil water flow directions. However one should be aware that the lines do not represent equipotentials.

The elevation, at which the matrix potential is zero corresponds to the depth of the watertable. Thus a perched water table can be observed, e.g. in Fig.3 at a depth of approximately 0.2 m below the surface 5.0 m from the trench (left side, left group). This fact was not reproduced by the simulation (right side, left group). The net rainfall is presented in the upper part of Fig.2. Each bold bar represents an hourly value. The actual value, which corresponds to the situation shown in the lower portion of Fig.3 and 4, appears in the rectangular window on the top.

Figure 3 depicts a situation at the end of March just one hour before rainfall starts. The watertable at midway between drains (0.5 m) is approximately 0.3 m above drain level. The matrix potentials (left group) are nearly parallel and almost not in equilibrium with the gravitational potential. Therefore the hydraulic heads give almost vertical lines (zero gradients marking no flow downwards). In horizontal direction the pronounced gradients indicate a horizontal water flow towards the drain pipe and only in the vicinity of the drain (between 0.3 m distance and drain pipe) radial flow appears. This fact is more pronounced in the simulation than in the measured values (left side). With a suction of approximately 40cm to 50cm in the upper 0.20 m layer the trafficability is still not possible.

Figure 4 gives the situation three hours later, after 7mm of rainfall have fallen. The observed values show only a slight rise in the watertable but a distinct change of the potential distributions. In the upper 0.40 m of the soil the matrix potentials nearly approach the zero-potential line and consequently the hydraulic gradients reach the value of one. The unsaturated zone becomes nearly saturated, with an evident downward flow, a tendency which is less pronounced by the simulation. In contrast to observed values the model suggests an important rise of the watertable.

CONCLUSION

The process of recharge and discharge of water in systematically drained soils is governed by a number of factors like rainfall intensity, evapotranspiration, soil characteristics and drain design like drain spacing, - depth and - diameter. The two-dimensional model, solving the Richards equation by means of finite differences, coupling the saturated and unsaturated soil zones, proved to be satisfactory for the prediction of hydraulic potentials in the upper layers of drained soils. This, in spite of the fact, that the resolution of the applied grid was crude in order to handle a long term forecasting by a personal computer within an acceptable running time. Deviations of simulated values from the field data were within the range of 10%. The calibration of the model by "trial and error fitting" of the soil characteristics proved to be delicate. Apart from drain discharge calculations the model is intended to provide estimates of agronomic benefits of agricultural drainage.

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SUB-SURFACE DRAINAGE WITH LINEAR VERTICAL HETEROGENEITY

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ABSTRACT. The presently available analytical solutions of sub-surface drainage are based on the assumptions that the soil is homogeneous and isotropic. In nature, however, soils are generally observed to occur according to several trends of variation in heterogeneity. In the present study, analytical solutions have been obtained for steady state water table profile with constant rate of replenishment between two parallel drains fully penetrating upto the impermeable layer consisting of a soil with hydraulic conductivity linearly decreasing with depth.

RESUME. *Les solutions analytiques du drainage souterrain, actuellement disponibles, sont basées sur l'hypothèse que le sol est homogène et isotropique. Dans la nature, toutefois, on constate généralement que les sols se présentent selon plusieurs tendances de variation d'hétérogénéité. Dans la présente étude, des solutions analytiques ont été obtenues pour un profil de nappe phréatique en régime permanent avec un taux constant de réapprovisionnement entre deux canaux de drainage parallèles pénétrant complètement jusqu'à la couche imperméable se composant d'un sol avec une conductivité hydraulique décroissant linéairement avec la profondeur.*

INTRODUCTION

Sub-surface drainage problems occur in a variety of soil hydrological conditions. Most of the analytical theories developed for drainage, however, consider the soil to be homogeneous and isotropic. Such soils do occur commonly in nature. But in various parts of the world soils with various types of heterogeneity, horizontal and vertical are also observed. Anisotropic soils have also been found to occur in nature.

The most commonly occuring soils in alluvial plains have soils with vertical heterogeneity. Various models of vertical heterogeneity can be conceived such as oils having soil layers with hydraulic conductivity varying exponentially with depths and soils having hydraulic conductivity varying linearly with depth. In the present study analytical solutions have been obtained for steady state drinage with constant replenishment between two parallel ditches, having a soil with its hydraulic conductivity varying linearly with depth.

The earlier works of drainage of vertically heterogeneous soils relate mostly to layered soils, even though there is mention of various patterns of vertical heterogeneity varying continuously with depth since quite some times. Kochina (1962) obtained seepage relations for soils with linearly varying vertical heterogeneity and for layered soils. Kochina (1962) refers the introduction of Girinsky Potential concept to Girinsky (1946). This concept has been applied in a series of papers by Youngs (1965, 1966, 1980) for study of seepage of soils with varying nature of heterogeneity.

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Kirkham (1951) obtained relationship of seepage of ponded water to drains in a layered soil. Kirkham (1954) also obtained solution from ponded source and upward artesian seepage to drain tube in layered soils. Ernst (1956, 1962, 1963) obtained solutions for drainage of layered soils by extending Hooghoudt (1940) approach. Dagan (1965) obtained analytical solutions for drainage of a two layered soil when spacing was expressed alongwith a number of other variables. Toksoz and Kirkham (1971a) obtained solutions for drainage of two layered and three layered soils with drains lying in the upper stratum. Later Toksoz and Kirkham (1971b) prepared a set of nomographs based on their earlier solution for finding drain spacing of two layered soils.

Najamii et.al. (1978) obtained analytical solution for steady state drainage of a two layered soil having replenishment from above as well as artesian flow from below.

Singh and O'Callaghan (1978) carried out sand tank model studies on steady state and unsteady state sub-surface drinage of layered soils. Though their experiments provide a good insight into the physical problem they cannot be used as such for varying configurations for sub-surface drainage of layered soils. Walter et al. (1978) field studies similarly provide an insight into sub-surface drainage of layered soils but cannot be used as such for design or field use.

Khan et al. (1989) carried out experimental simulation of steady state sub-surface drinage of a two layered soils on a vertical Hele-Shaw model and experimentally verified the Kirkham and Toksoz (1971a) solution.

Agarwal and Chauhan (1991) obtained solution for transient drainage of a two-layered aquifer bounded by two canals using Girinsky potential. Sharma et al. (1991) obtained steady state solution for drainage of a two layered soil using Girinsky potential. Armstrong et al. (1991) obtained non-steady state solution for predicting water tables between two drains with the soil having a hydraulic conductivity decreasing exponentially with depth.

From a review above, it is seen that several studies of sub-surface drainage with vertical heterogeniety for steady state as well as unsteady state conditions are available. Most of the drainage theories available, however, are applicable for layered soils except the one by Armstrong et. al. (1991) which assumes the soil to have its hydraulic conductivity decreasing exponentially with depth.

The simplest model of vertical heterogeneity besides layered soils seems to be the one in which the hydraulic conductivity decreases linearly with depth. In the present study the solution for steady state drinage for such a soil has been onbtained by using Girinsky potential and the generalized Boussinesq equation given by Kochina (1962) and Aravin and Numerov (1965).

PROBLEM FORMULATION

The proposed drainage problem is described in Figure 1 and is governed by the following assumptions :

1. Two parallel open ditch drains cut through the soil reaching upto the impermeable layer.
2. The phreatic aquifer lies over a horizontal impermeable bed.
3. The drainage medium between the ditches over the impermeable layer has hydraulic conductivity linearly decreasing with depth given by,

$$K(z) = K_0 z \tag{1}$$

Where, K is the hydraulic conductivity at a given height, Z above the impermeable layer and K_0 is a proportionately constant describing the linearty, having a value zero at the impermeable layer.

4. A constant rate of rainfall/irrigation excess percolates vertically downwards joining the water tabe and building up a steady state phreatic profile.

5. Dupuit-Forchheimer assumptions are valid.

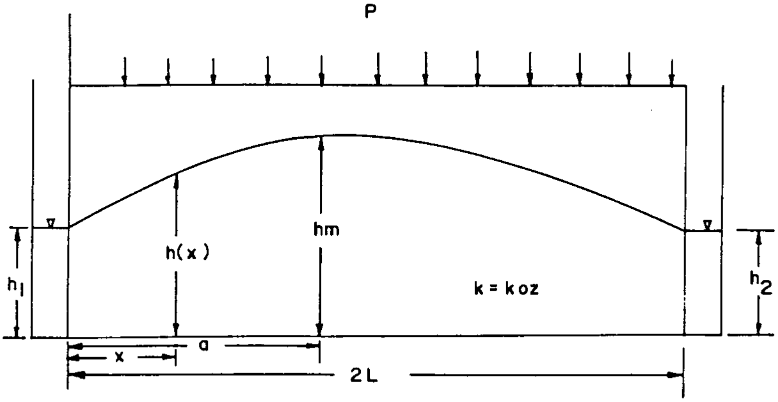

Figure 1. Definition sketch

The phreatic surface is assumed to be described by the generalized Boussinesq equation based on Girinsky potential given by Aravin and Numerov (1965) as:

$$\alpha^2 \frac{\partial G}{\partial x^2} + \beta = \frac{\partial G}{\partial t} \tag{2}$$

$$\alpha^2 = \frac{1}{m(h)} \int_0^h K(z)\, dz \tag{3}$$

$$\beta = \frac{P}{m(h)} \int_0^h K(z)\, dz \tag{4}$$

Where, P = constant replenishment, m(h) = specific yield of the soil and K(z) = hydraulic conductivity varying vertically with depth.

Girinsky potential is defined by:

$$G(x) = \int_0^h K(z)\,(h-z)\,dz$$

which describes the phreatic surface for vertically heterogeneous flow region.

STEADY STATE SOLUTION

For the assumed functional form of vertical heterogeniety given by Eq. (1),

$$G(x) = \int_0^h K_o\, z\,(h-z)\,dz = \frac{K_o h^3}{6} \tag{5}$$

For steady state conditions Eq. (2) may be written as:

$$\frac{\partial^2 G}{\partial x^2} + P = 0 \tag{6}$$

Integrating Eq. (6) and equating with (5) gives,

$$G(x) = \frac{K_o h^3}{6} = \frac{-Px^2}{2} + C_1 x + C_2 \tag{7}$$

$$\text{or, } h^3 = -\,A\,x^2 + Bx + c \tag{8}$$

Where,

$$A = \frac{3P}{K_o} \tag{9}$$

Solutions for different boundary conditions may be obtained as below :

Drains with Water at Unequal Levels

Boundary conditions may be considered as,

$$h(0) = h_1 \tag{10}$$

$$h(2L) = h_2$$

Putting boundary conditions (10) in Eq. (8) gives,

$$C = h^3_1 \tag{11}$$

$$B = \frac{h^3_2 - h^3_1}{2L} + 2AL \tag{12}$$

The phreatic surface is given by putting (11) and (12) in Eq. (8) as:

$$h^3 = \frac{3D}{K_o}(2Lx - x^2) + \frac{h^3_2 - h^3_1}{2L}x + h^3_1 \tag{13}$$

Water Divide

This is obtained by putting $\left.\frac{dh}{dx}\right|_{x = a} = 0$ in Eq. (3) as,

$$a = \frac{h^3_1 - h^2_2}{2AL} + L \tag{14}$$

Ditch Spacing in Bilevel Drainage

The drain spacing is obtained in an implicit way by putting h (0) - h_m in Eq. (8). Considering Q = 2 PL and the above substitution, the relationship between L, h_m and Q is obtained implicitly for bilevel drainage as:

$$\frac{K_o}{GL}(h^3_2 - h^3_1) + Q^2 = \frac{2K_o}{3L}Q(h^3_m - h^3_1) \tag{15}$$

Discharge

This is obtained by putting,

$$Q = \frac{sG}{sx} = \frac{K_o h^2}{2}\frac{sh}{sx} = \frac{K_o}{6}(B - 2Ax) \tag{16}$$

Drains with Equal Water Levels

The different relationships are obtained by putting,

$$h_1 = h_2 = h_d \tag{17}$$

Phreatic Surface

Putting (11) and (12) in Eq.(9) for conditions (17) gives,

$$h^3 = \frac{3P}{K_o}(2Lx - x^2) + h^3_d \tag{18}$$

Ditch Spacing

Putting h(L) = h(m) in Eq. (18) gives,

$$h^3{}_m = \frac{3P}{K_o} L^2 + h^3{}_d$$

$$L = \frac{2K_o}{3Q} (h^3{}_m - h^3{}_d) \tag{19}$$

where Q = 2 PL. The same expression can be obtained by putting condition (17) in Eq.(13),

$$Q = PK_o (L - x) \tag{20}$$

Drains with no Water

Phreatic surface

Putting h_d = O in Eq.(18) gives,

$$h^3 = \frac{3P}{K_o} (2Lx - x^2) \tag{21}$$

Drain Spacing

Putting $h_d = 0$ in Eq. (19) gives,

$$L = \frac{2K_o h^3{}_m}{3Q} \tag{22}$$

STEADY STATE WATER TABLE NOMOGRAPHS

For convenience of practical use the steady state solution given by Eq. (18) after dividing by h_d and putting X = x/2L can be written in demonstration form as:

$$\frac{h^3}{h^3{}_d} = \frac{3P}{K_o h^3{}_d} (2X - X^2) - 1 \tag{23}$$

The dimensionless water table profile with the selection of a set of normally occuring soil hydrological parameters and drainage geometries can be represented into a set of useful nomographs given in Figures 2-5.

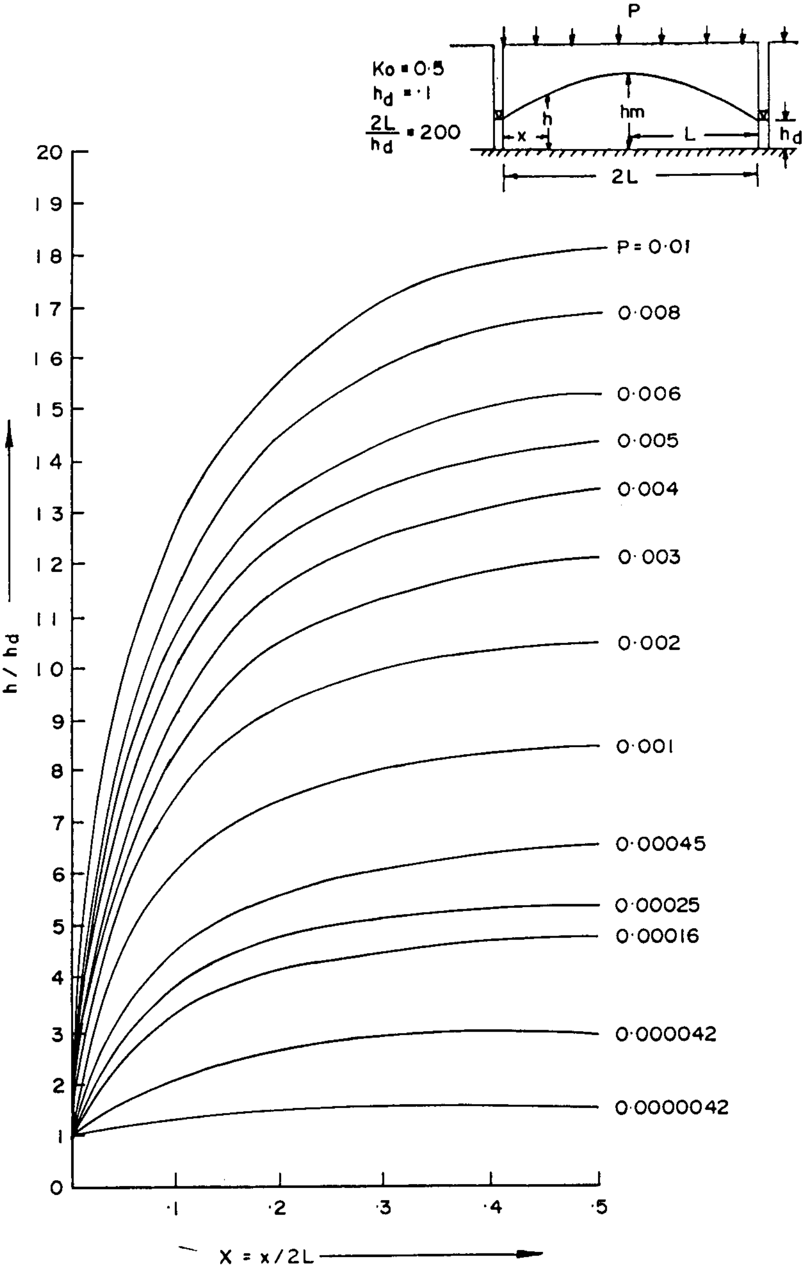

Figure 2. Phreatic surface for different recharges

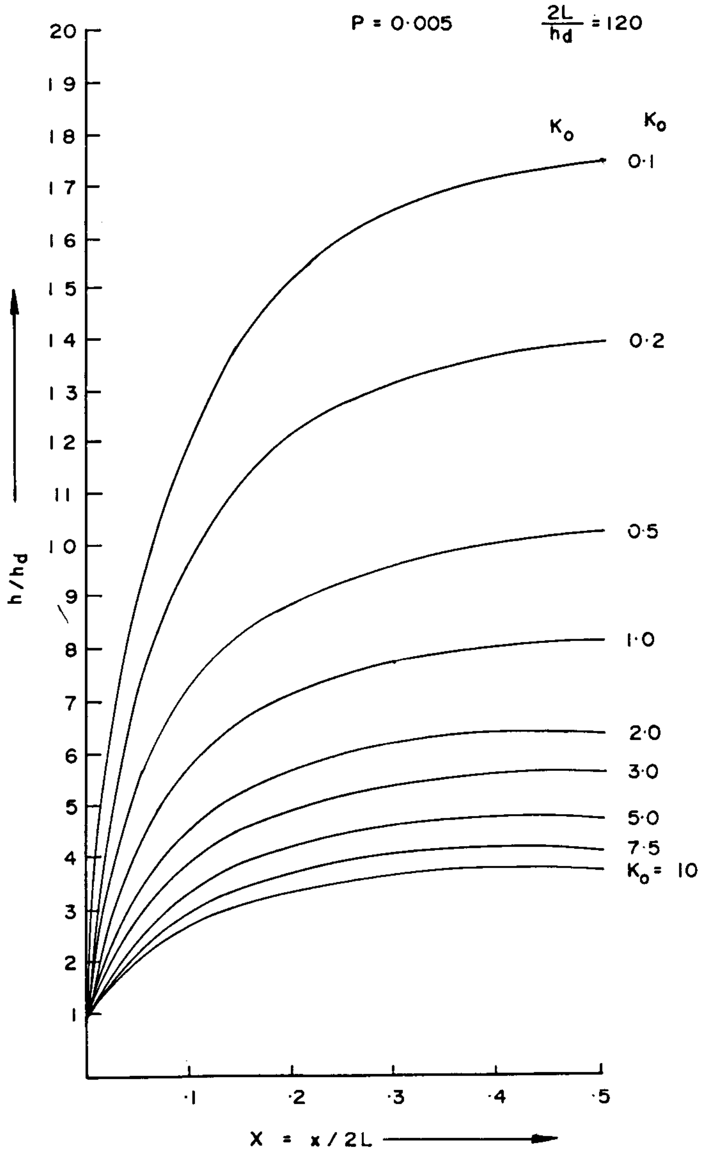

Figure 3. Water table height for varying recharges

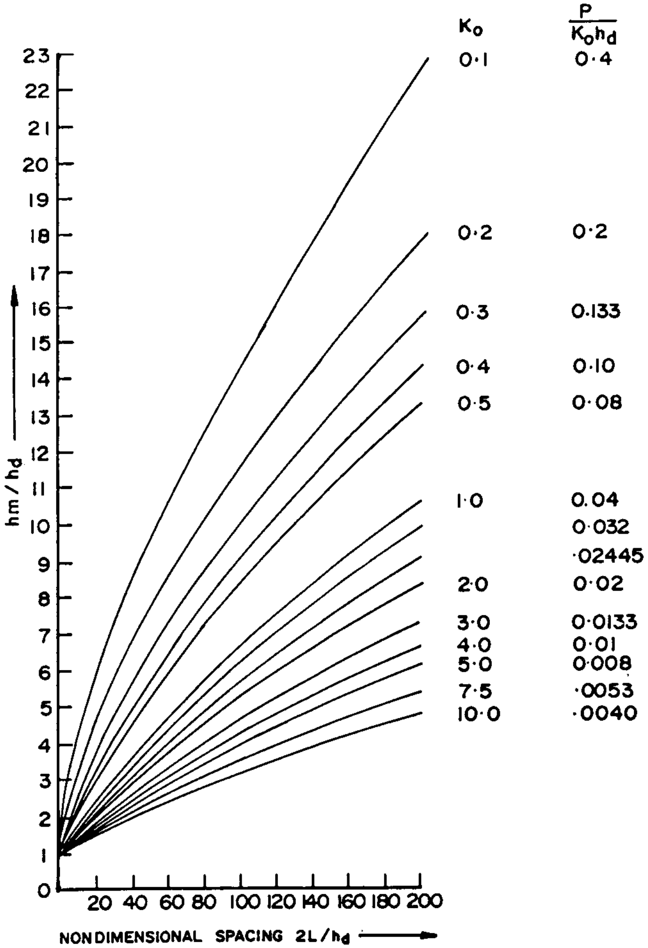

Figure 4. Maximum water table heights for varying hydraulic conductivity

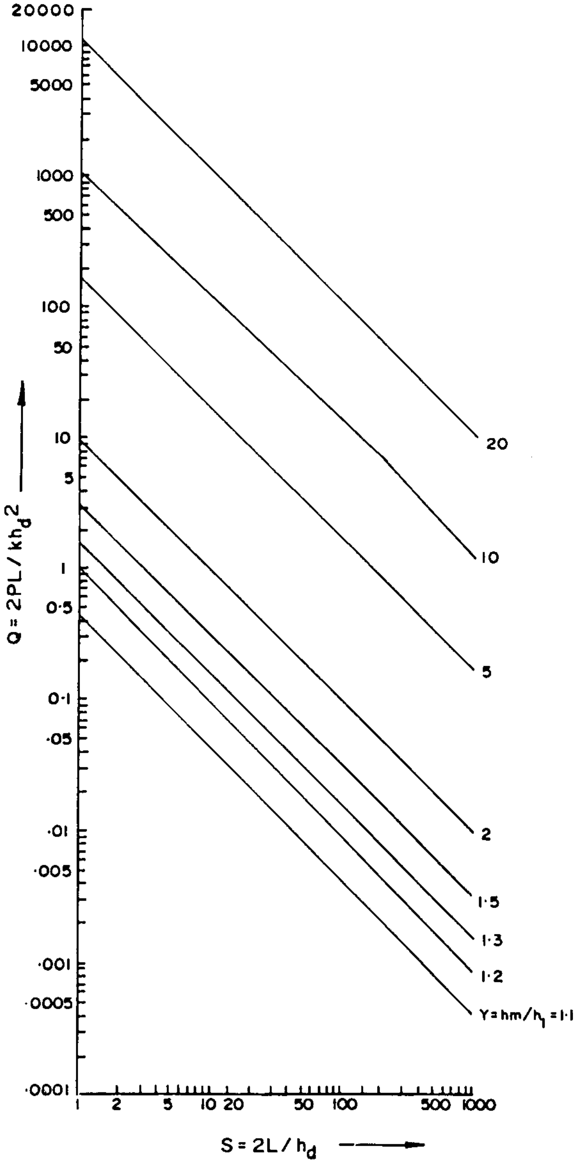

Figure 5. Discharge versus spacing

Illustrative Examples

A drainage system is to be designed in a soil having hydraulic conductivity represented by K(z)=0.462 z. Soil receives 150 mm irrigation at an interval of 20 days with 30 percent deep percolation. It is required to determine the spacing between the drains. The impermeable layer is assumed to exist at a depth of 0.8 m. Water level in ditch is .2 m in the first case and zero depth in the second case.

Application of theoretical solution

Case I

Recharge = 150 x.3 = 45 mm
Recharge Rate = 45 / 20 = 2.25 mm/day = 0.00225 m/day
Root Zone Depth 0.8 m = hm
Water table depth in ditch = 0.2 m = hd

From Eq. (14) spacing.

$$2L = \frac{4K_o}{3Q}(h^3{}_m - h^3{}_d) = \sqrt{(h^3{}_m - h^3{}_d)\frac{4K_o}{3P}}$$

$$= \sqrt{(.8^3 - .2^3)\frac{4 * .46}{3 * .00225}} = 11.721 \text{ m}$$

Case II

Ditch water level zero. Use of Eq. (22) gives,

$$2L = \frac{4K_o}{3Q}\, h^3{}_m = \sqrt{(h^3{}_m)\frac{4K_o}{3P}}$$

$$= \sqrt{\frac{4 * .46x .\, 8^3}{3 * .00225}} = 11.813 \text{ m}$$

Use of non-dimensional Figure 4

Find $\frac{P}{K_o\, h_d} = \frac{.00225}{.46 * .2} = 0.07445$

and $\frac{h_m}{}h_d = \frac{.8}{.2} = .4$

Locate $\frac{P}{K_o h_d} = .02445$ lime and $\frac{h_m}{h_d} = 4$

On vertical axis, locate the intersection point and come down to horizontal axis intersection at 58.

$$\frac{2L}{h_d} = 58, \text{ or } 2L = 58 * .2 = 11.8 \text{ m}$$

EXPERIMENTAL VERIFICATION OF THEORY

It is desirable to test the analytical solution for the steady state water table profiles through experimental observations. However, no field data were available for such a flow system. Because of lack of any field experimental data the flow system was simulated on a vertical Hele-Shaw model.

Vertical slow viscous models have been used for obtaining experimental solution as well as for verification of analytical solutions in a number of studies in the past. But most of the simulations have been done for either homogeneous isotropic soil or for layered soils, homogeneous and isotropic within each layer. Little work appears to have been done for simulation of flow system in which there is a vertically varying hydraulic conductivity. In case the hydraulic conductivity is constant the flow region can be simulated by maintaining a constant space between the two plates and the hydraulic conductivity is given by,

$$K_m = \frac{b^2 g}{12V} \tag{24}$$

Where, K_m is the hydraulic conductivity of the model, b is the spacing between the two plates and V is the kinematic viscosity.

Simulation of Model with Hydraulic Conductivity Linearly Decreasing with Depth

Two parallel plates 184 cm long and 55 cm wide were used for the model. It was assumed that the hydraulic conductivity remainted constant at a given height in the horizontal direction. Thus to obtain a hydraulic conductivity varying linearly from a maximum at the top to a zero value at the bottom required the spacing to be varied in the model as,

$$b = CZ^{1/2} \tag{25}$$

Considering arbitrarily the maximum spacing at the top as 2mm at a height of 55cm and a minimum spacing of 0 cm at the bottom the value of C = .027. The spacings at different points along the vertical direction were maintained according to Eq. (25) by putting brass washers between the plates and keeping the same constant along the length. After the fabrication of the model known volume of oil was poured in the model and noting the height it filled the model the spacing at different height was estimated. The designed and observed spacing and the hydraulic conductivities are given in Table 1.

Sl. No.	Oil Volume poured (cc)	Height observed (cm)	Designed spacing (mm)	Spacing observed (mm)	Hydraulic conductivity at observed heights $K(z) = K_0 z$ (cm/min)
1.	300	20.4	1.22	1.20	4.23
2.	490	28.1	1.43	1.42	5.82
3.	680	34.7	1.59	1.60	7.19
4.	880	41.1	1.73	1.74	8.51
5.	1080	47.5	1.86	1.85	9.84
6.	1170	50.1	1.91	1.9010.37	

Table 1. Observed and designed model spacing and hydraulic conductivity variation with height.

It may be seen that the fabricated spacings are reasonably close to the designed ones.

For a linear variation of hydraulic conductivity:

$$K(z) = K_0 z = \frac{b^2 g}{12V} = \frac{(Cz^{1/2})^2\, g}{12V} = \frac{C^2 z\, g}{12V} \tag{26}$$

or

$$K_0 = \frac{c^2 g}{12V} \tag{27}$$

The viscous fluid used in the model was HP 140 gear oil. The experiments were conducted at 23 ±0.5 ^{0}C. At this temperature, the kinematic viscosity was observed as 17.25 stokes. Using eq. (27) K_0 = .2073 per minute. Variation of spacing and hydraulic conductivity with depth in given in figure 6.

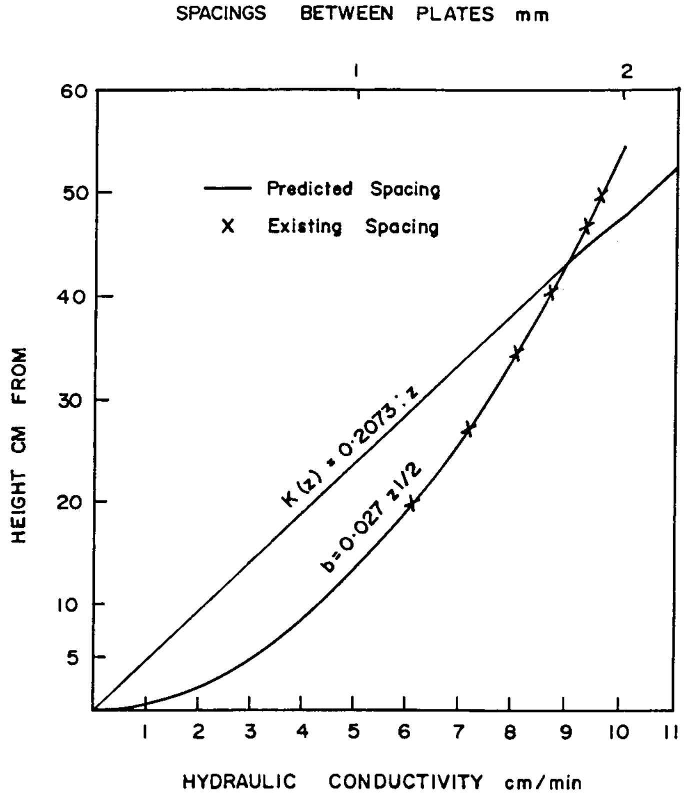

Figure 6. Model hydraulic conductivity and spacing variation with height

Results and Discussions

Water Table heights

The observed and predicted water table heights for two conditions with no water in the ditch, $h_d = 0$, and a given height of water $h_d = 25$ cm are given for two recharge locations in Table 2.

	X = x/2L											Recharge Location
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	
	Case I: Water Level in the ditch h_d = 0 cm											
Observed (cm)	35.0	41.2	45.9	48.5	49.5	50.5	49.5	48.5	45.9	41.2	34.9	
	P = 0.728 cm/min. (b = 0.192 cm)											At the maximum phreatic surface
Predicted (cm)	0.0	31.8	38.4	42.2	44.1	44.7	44.1	42.2	38.4	31.9	0.0	
Deviation (%)	100.0	-22.9	-16.4	-13.1	-10.9	-11.5	-10.9	-13.1	-16.4	-22.9	100.0	At the average spacing between top phreatic surface and imprevious layer
	P = 1.093 cm/min. (b = 0.128 cm) spacing between											
Predicted water table heights	0.0	36.4	44.1	48.3	50.5	51.2	50.5	48.3	44.1	36.4	0.0	
Deviation (%)	100.0	-11.7	-3.9	-0.5	1.9	1.3	1.9	-0.5	-3.9	-11.7	100.0	
	Case II: Water Level in the ditch h_d = 25 cm											
Observed (cm)	35.0	41.8	45.5	47.8	48.8	49.3	48.8	47.8	45.6	41.8	35.0	
	P = 0.674 cm/min. (b = 0.189 cm)											At the maximum phreatic surface spacing
Predicted (cm)	25.0	35.7	40.9	43.9	45.6	46.1	45.6	43.9	40.9	35.7	25.0	
Deviation (%)	-28.6	-14.7	-10.1	-8.0	-6.5	-6.4	-6.5	-8.0	-10.1	-14.7	-28.6	
	P = 1.012 cm/min. (b = 0.126 cm)											
Predicted water table heights	25.0	39.2	45.6	49.3	51.2	51.9	51.2	49.3	45.6	39.2	25.0	At the average spacing between top phreatic surface and imprevious layer
Deviation (%)	-28.5	-6.2	0.3	3.1	5.0	5.2	5.0	3.1	0.3	6.2	28.5	

Table 2. Observed and predicted water table heights for different ditch of water levels.

Considering the case I and recharge at maximum phreatic surface with $h_d = 0$, it is observed that the predicted heights have deviation of around - 11.5 percent in the middle and around - 22.86 percent near the drains. However, for the case with $h_d = 25$ cm and recharge considered at maximum height the deviations are lesser, about 5.2 percent in the middle and more i.e. - 28.57 percent at the ends.

It is thus observed that the observed results improves as the water level in ditch increases. This may be because of reduction of net effective head in the middle leading to the streamlines being more horizontal. But in general the errors in predicted values are of higher order both in the middle and at the ends.

Improvement in Results

A difficulty is observed in simulation of replenishment in the flow system. The replenishment requires consideration of area in which water is received. This area varies with height. For a given steady state profile for a prevailing replenishment the receiving area at maximum height is more whereas at the level of phreatic surface near the drains it is much less.

Thus considering at higher heights for the same volume rate of replenishment, the replenishment rate will be less if considered at higher heights and more if considered at lesser heights.

Replenishment actually means production of fluid coming vertically from above or being generated in the flow region. One possibility is considering the recharge at average spacing between top phreatic surface and impervious layers. This may be obtained as,

$$\bar{b} = \frac{1}{h}\int_0^h b\,dz = \frac{2}{3}h^{1/2} \tag{28}$$

If recharge is considered at such a spacing of plates the results are found to reasonably improve for both the cases of flow systems considered.

CONCLUSIONS

Analytical steady state solutions were obtained for two parallel sub-surface drainage ditches reaching the impermeable layer and having a constant recharge in a soil in which the hydraulic conductivity linearly decreased with depth using generalized Boussinesq's equation. Nomographs were obtained for simplifying determination of drainage design parameters.

The flow system was simulated on a vertical Hele-Shaw model by appropriately increasing the vertical spacing of the model with heights. The phreatic surface predicted showed deviations in the observed profile increasing from the mid-point towards the ends. With the consideration of recharge at appropriate average spacing of the model the deviations in the results were found to reduce suggesting a possible improvement in simulation.

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GROUND WATER TABLE BEHAVIOR IN SUBSURFACE DRAINED LAND IN PRESENCE OF EVAPOTRANSPIRATION

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ABSTRACT. One of the processes known to influence ground water table behaviour in drained irrigated lands of arid and semi-arid regions is evaporation/evapotranspiration (ET). In order to quantify the contribution of evaporation/ET in lowering the water table, mathematical models have been developed utilizing 3 different techniques. In the first technique, a linearized Boussinesq equation with a linearly decreasing evapotranspiration as the sink term was solved to develop an analytical solution. Non-linear Boussinesq equation was solved numerically utilizing extrapolated Crank- Nicolson scheme. For this purpose, a functional relation which allowed evaporation/ET to reduce with depth to water table either linearly or curvilinearly was used. Finally, a simple approach of Bouwer and van Schilfgaarde was utilized. For this purpose, evapotranspiration-depth to water table relation was described by a piecewise linear function.

The proposed solutions based on the Boussinesq equation yielded almost identical results. After assigning relevant parameters, a comparison with existing models also indicated a good match between the proposed and the existing models. The solution proposed on the basis of Bouwer and Van Schilfgaarde approach, however, predicted a faster fall than other models. Field data and data from a sand tank model study were utilized to verify and test the models. A close agreement between the observed and predicted values has been obtained both with the sand tank and the field data. Calculations with some realistic set of parameters revealed that for semi-arid regions in India, it is possible to increase the drain spacing by about 18-25 per cent over and above the conventional design spacing.

RESUME. *Les études actuelles sur le drainage en Inde sont orientées vers la recherche de solutions optimales pour déterminer la profondeur et l'espacement des drains en vue d'économiser sur le coût. L'évapotranspiration est l'un des procédés qui influence le comportement du niveau de la nappe d'eau souterraine dans les terres drainées et irriguées des régions arides et semi-arides. Etant donné que les équations conventionnelles négligent cette composante, on suppose que l'erreur d'assortiment entre les valeurs observées de la profondeur de l' eau souterraine dans le cas des terres drainées et les valeurs prévues utilisant des équations conventionnelles pourrait être due à ce facteur. Pour quantifier la contribution de l'évapotranspiration à l'abaissement de la nappe d'eau, des modéles mathématiques ont été développés utilisant 3 différentes techniques. Pour chaque technique, une relation différente entre l'évapotranspiration et la profondeur de la nappe d'eau a été choisie. Dans la premiére technique, une équation linéarisée de Boussinesq avec un facteur d'atténuation a été résolue en vue de développer une solution analytique. Une évapotranspiration décroissant linéairement avec la profondeur de la nappe d'eau a été choisie pour définir le facteur d'atténuation. Dans le cas d'une version améliorée, l'équation non linéaire de Boussinesq a été résolue numériquement en utilisant l'algorithme de Crank- Nicholson. A cet effet, une relation fonctionnelle plus flexible*

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a été utilisée. Avec cette fonction, l'évapotranspiration décroit avec la profondeur de la nappe d'eau soit linéairement soit curvilinéairement. Finalement, une simple méthode de Bouwer et de van Schilfgaarde a été utilisée pour fournir une alternative plus simple à utiliser dans les projets. A cet effet, la relation entre l'évapotranspiration et la profondeur de la nappe d'eau a été décrite par une fonction linéaire.

Les solutions proposées sur la base de l'équation de Boussinesq ont produit des résultats à peu prés identiques. Aprés attribution des paramétres pertinents, une comparaison avec les modéles existants a aussi indiqué une bonne adaptation entre les modéles proposés et existants. La solution proposée sur la base de la méthode Bouwer et Van schilfgaarde conduit à une chute plus rapide par rapport aux autres modéles. Un modéle d'un réservoir de sable a été construit et utilisé pour étudier le comportement du niveau de la nappe d'eau souterraine aussi bien en présence qu'en absence de l'évapotranspiration. Des données recueillies sur le terrain depuis deux sites de drainage en Inde ont aussi été utilisées pour vérifier et tester les modéles. Une bonne adaptation entre les valeurs observées et prévues a été obtenue avec le réservoir de sable et les données sur le terrain.

Les critères de conception de drainage actuellement utilisés en Inde, s'ils sont appliqués avec ces équations produiraient un espacement de drain relativement plus élevé que celui des équations actuellement utilisées dans lesquelles l'évapotranspiration n'a pas été comprise. Les calculs avec un jeu réaliste de paramétres ont montré qu'il est possible d'augmenter l'espacement des drains d'environ 18 à 25 pour cent au delà de l'espacement nominal conventionnel.

INTRODUCTION

Horizontal sub-surface drainage is a recognized and increasingly practiced method of lowering water table and removing the excess soluble salt from the root zone. Many steady state and non-steady state equations have been developed for drainage design in the last 50 years. But despite the importance of sub-surface drainage and availability of the research information on the subject, most of the drainage recommendations have been developed by experience. Though many equations show good agreement with the studies conducted under controlled condition, they are less accurate under the field condition. The probable reason for this inaccuracy in addition to soil heterogeneity may be that under field condition many additional processes than tile flow come into existence. For example, some of the processes are evaporation/ET from shallow ground water table, non tile seepage and flow from unsaturated zone (which affects the drainable porosity). The objective of the present study is to highlight the role of evaporation/ET on the water table draw down in drained lands and to evaluate its effect on the drainage design.

Role of evaporation in drainage design

Role of evaporation/ET in drainage design was realized as early as in 1956 (van Schilfgaarde et al., 1956). An equation which takes into account the effect of the evaporation/ET in drainage design was first developed in 1962 (Hammad, 1962). Skaggs (1975) assumed that evaporation occurs at a constant rate while solving the Boussinesq equation numerically for finding water table draw down between two parallel drains. Ayars and Mcwhorter (1985) found that by taking into account evapotranspiration, design drain spacing could be increased to 145 m compared to 39 m when evapotranspiration component is not included. A comprehensive work on this aspect has been conducted at the Central Soil Salinity Research Institute, Karnal (India) which is a subject matter of discussion in this paper.

APPROACHES TO PREDICT GROUND WATER TABLE BEHAVIOUR

Boussinesq equation and sink term for evaporation/ET

The Boussinesq equation for one dimensionel flow when the ground water body is influenced by evaporation/ET can be written as

$$K\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) - P = f\frac{\partial h}{\partial t} \qquad (1)$$

in which K is the hydraulic conductivity, LT^{-1}; h is the height of the water table; f is the drainable porosity which is assumed to be constant, dimensionless; x is horizontal space co-ordinate, positive towards right; t is the time,T and P is a sink term which represents evaporation/ET. A linearized version of eq.(1) is written as

$$\frac{\partial^2 h}{\delta x^2} - \frac{P}{h'} = \frac{f}{h'}\frac{\partial h}{\partial t}$$

where h'= KD such that D is the average depth of saturated aquifer and hence h' is considered as a constant. In the process of linearization, it is assumed that the variation in h is small as compared to $\partial h/\partial x$.

Functional relations between evaporation rate and depth to water table

In the present formulations, depth to water table has been taken as a major factor that influences the rate of evaporation/ET. The following functional relations between the rate and depth to water table were selected.

$$E_d = E_o\text{-}b\,d \qquad (3)$$

here E is the evaporation rate, (LT^{-1}) such that E_o and E_d represent the evaporation rate when the ground water table is at the soil surface and at d cm below the soil surface respectively and b is a constant (T^{-1}) which governs the decrease in the evaporation rate with depth to water table.

In the case of numerical solution of the Boussinesq equation, the functional relation between the evaporation rate and the hydraulic head is described as

$$\frac{E(h)}{E_o} = \frac{h/h_o}{\frac{h}{1-Q} + (1 - \frac{h}{h_o})/z} + Q \qquad (4)$$

where Q= $E(h)/E_o$ corresponding to the water table at drain depth i.e. h=0, h_o is the initial hydraulic head and Z is a constant. The shape of the curve will depend upon the value of Z. The curve will be linear, concave or convex depending on whether Z= (1-Q) or Z <(1-Q) or Z >(1-Q) (Figure 1a).

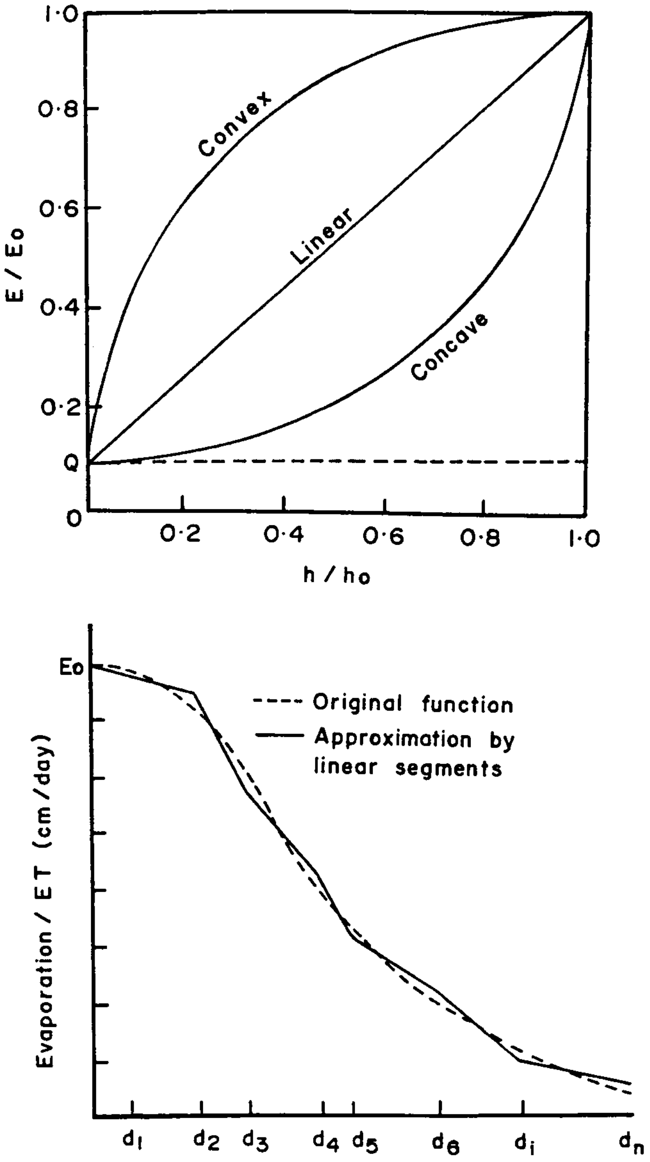

Figure 1. Functionnal relation between evapotranspiration ET and depth to water table/ hydraulic head (a) linear and curvilinear (b) piecewise linear

For the third case, Bouwer and van Schilfgaarde (1963) approach was utilized. A piecewise linear model is proposed to describe the functional relation. According to this proposal any rectifiable curve could be approximated by piecewise linear segments.

$$ET_{d1}=ET_o-b_1 \qquad d\ 0<d<d_1 \qquad (5)$$

$$ET_{d2}=ET_o-b_1d_1-b_2(d-d_2) \qquad d_1<d\leq d_2 \qquad (6)$$

$$ET_{di}=ET_o-b_1d_1-b_2(d_2-d_1)-\ldots b_i(d-d_i) \qquad d_{i-1}<d\leq d_i \qquad (7)$$

$$ET_{dn}=ET_o-b_1d_1-\ldots-b_n(d-d_n) \qquad d_{n-1}<d\leq d_n \qquad (8)$$

In these equations, ET_{di} is the evaporation/ET for segment i, d_i is the depth to water table, ET_o is the ET when the water table is at the soil surface, and b_i are the regression constants. All values with negative or zero subscripts are treated as zero. The parameter n is the total number of segments into which a rectifiable curve should be divided to get a close approximation of the exact relation (Fig. 1b). Equation (3) and eqs. (5) to (8) could be related to hydraulic head, once d is replaced by (h_o-h). By adjusting the values of b_i, d_i and n, any curve could be approximated with reasonable accuracy.

ANALYTICAL AND NUMERICAL SOLUTIONS

The initial and boundary conditions to solve the Boussinesq equations are given as follows.

$$h(0,t)= g_1\ (t), \qquad t>0 \qquad (9a)$$

$$h(l,t)= g_2\ (t), \qquad t>0 \qquad (9b)$$

$$h(x,0)= g_3(x), \qquad 0\leq x\leq L \qquad (9c)$$

where $g_1(t)$ and $g_2(t)$ are the variable hydraulic heads at the drain at x=0 and x=L and $g_3(x)$ describes the initial hydraulic head between the two drains. For a initially flat water table and for an instantaneous drop in the water table from h_o to 0 at x=0 and $\partial h/\partial x=0$ at x=L/2, the analytical solution of eq. (2) is given as

$$h = -\frac{A_1}{A_2}\left[\frac{\cosh\,(L/2-x)\,(A_2)^{1/2}}{\cosh\,(L/2)\,(A_2)^{1/2}} - 1\right] - \frac{4\,A_1\,L^2}{\pi}$$

$$\sum_{n=0}^{\infty}\frac{1}{ZL}(-1)^n \exp\left\{\left[-(2n+1)^2\,\pi^2 + (-A_2)\,L^2\right] \cos(2n+1)\,\pi\,(L/2-x)\right.$$

$$+\,h_o - \left\{h_o \sum_{n=0}^{\infty}(-1)^n \operatorname{erfc}\frac{(2n+1)L/2\ -\ (L/2-x)}{2\sqrt{(Et)}}\right. +$$

$$\left. h_o \sum_{n=0}^{\infty}(-1)^n \operatorname{erfc}\frac{(2n+1)\,L/2\ +\ (L/2-x)}{2\sqrt{(Et)}}\ \right\} \qquad (10)$$

such that,

$$E=KD/f;\ A_1=E_o/KD;\ A_2=b/Kd \text{ and } Z=[L^2(-A_2) - (2n+1)\pi^2](2n+1)$$

some special cases of interest can be obtained by incorporating $E_o=0$, or by taking a value of b such that b approaches zero (say=0.000001).

To obtain the numerical solution, eq. (4) was incorporated in eq. (1) as a sink term and extrapolated crank- Nicolson finite difference scheme was applied to get the solution subject to the initial and boundary conditions given by eqs. (9a) to (9c).

The solution based on Bouwer and van Schilfgaarde (1963) approach subject to the sink term described by eq. (5) to eq. (8) is given as follows

Case 1: $r^2>4mp$

For this case, the final solution iswritten as:

$$t = \sum_{i=1}^{n} \frac{L^2Cf}{A_i} \ln\left[\left(\frac{B_i - A_i}{B_i - A_i}\right)\left(\frac{C_i + A_i}{C_i - A_i}\right)\right] \tag{11}$$

such that

$$A_1 = [(8\,K_2\,d_e + L^2\,b_i)^2 - 16\,K_1(ET_{di-1} - b_i\,h_{i-1})L^2]^{1/2} \tag{12}$$

$$B_i = 8\,K_1\,h_{i-1} + 8\,K_2\,d_e + L^2\,b_i \tag{13}$$

$$C_i = 8\,K_1\,h_i + 8\,K_2\,d_e + L^2\,b_i \tag{14}$$

$$r = 8\,K_2\,d_e + L^2\,b_i, \qquad m = L^2\,(ET_o + b_1\,h_o)$$

$p = 4K_1h_2$; C = constant and K_1 and K_2 are the hydraulic conductivities of the layers below and above the drain.

Case 2: $r^2 < 4mp$

For such cases where $r^2<4mp$ the solution could be written as:

$$t = \sum_{i=1}^{n} \frac{2L^2Cf}{P_i} [\tan^{-1}(M_i / P_i) - \tan^{-1}(N_i / P_i)] \tag{15}$$

Here

$$P_i = [16\,K_1\,(ET_{di-1} - b_i\,h_o)\,L^2 - (8\,K_2\,d_e + L^2\,b_i)^2]^{1/2} \tag{16}$$

$$M_i = 8\,K_1\,h_{i-1} + 8\,K_2\,d_e + L^2\,b_i \tag{17}$$

$$N_i = 8\,K_1\,h_i + 8\,K_2\,d_e + L^2\,b_i \tag{18}$$

For n=1, ET_o=0, b_1=0 and K_1=K_2, eq. (11) as well as eq. (15) reduce to the well known Bouwer and van Schilfgaarde (1963) equation . For a single linear segment when q=0, Bouwer and van Schilfgaarde (1963) approach yields

$$t = \frac{cf}{bE_o} \ln \frac{E_o}{bE_oh+E_o-bE_oh_o} \qquad (19)$$

RESULTS AND DISCUSSIONS

To illustrate the effect of evaporation in lowering the water table, time required to lower the water table to various hydraulic heads was calculated when evaporation alone is contributing (eq. 19), equation of Bouwer and van Schilfgaarde (1963) when tile flow alone is operative and both tile flow and evaporation are operative (eq.11). For this example, time to lower the water table by 30 cm, is nearly 4 days, 1.8 days and 1.4 days for evaporation only, tiles only and when the tiles and evaporation act simultaneously.

Analytical solution

Analytical solution given by Eq. (10) has been derived to account for linearly decreasing evaporation rate. Special cases can be derived when evaporation occurs at constant rate or when the process of evaporation is not taken into account. A comparison of the special case of eq. (10) with E_0=0 shows a close agreement with an equation of Glover and Dumm in which case also evaporation is not accounted for. Similarly, the case for which evaporation occurs at a constant rate was compared with the solution derived on the basis of Bouwer and van schilfgaarde (1963) approach. When time lag between the instantaneous drop at the boundary and the start of flow at the centre of the drain is taken into account, a close agreement between the two solutions was obtained.

Numerical solution

The numerical solution of the Boussinesq equation with the sink term as described by eq. (4) was tested with the solution of Singh and Jacob (1976). Absolute percentage error of the numerical solution compared to the analytical solution of Singh and Jacob (1976) were 1.96 per cent, 2.72 per cent and 0.51 per cent respectively for a concave, linear and convex function for which values of Z in eq. (4) were taken as 0.0001, 1.0 and 99.0 respectively. The data from a sand tank model study was utilized to test the numerical solution. The functional relation which described evaporation under the test conditions most accurately is given as follows:

$$\frac{E}{0.01} = [\frac{h/1.22}{h/1.22(1-0.20) + (1-h/1.22)/0.30} + 0.20] \qquad (20)$$

As the drainable pore space was also found to be a function of the hydraulic head (Pandey et. al. 1992), the numerical solution allowed for this change. The comparison of the hydraulic heads at different times between the numerically computed and observed value were made at 3 different distances from the drain i.e. 0.5 m, 2.2 m and 4.33 m. It was seen that for all the three distances from the drain, the numerically predicted hydraulic heads, simulated the observed data at all times in a far better way as compared to the situation when f was taken as a constant and evaporation was neglected. For the sake of brevity, observed and predicted values of the hydraulic head at 2.2 m away from the drain are shown in Fig. 2. In terms of magnitude, the average absolute deviation between the observed and the predicted hydraulic heads at 0.50, 2.20 and 4.33 m away from the drain are respectively, 0.28, 2.85 and 3.28 cm for the former case compared to 12.70, 32.50 and 41.00 cm for the latter.

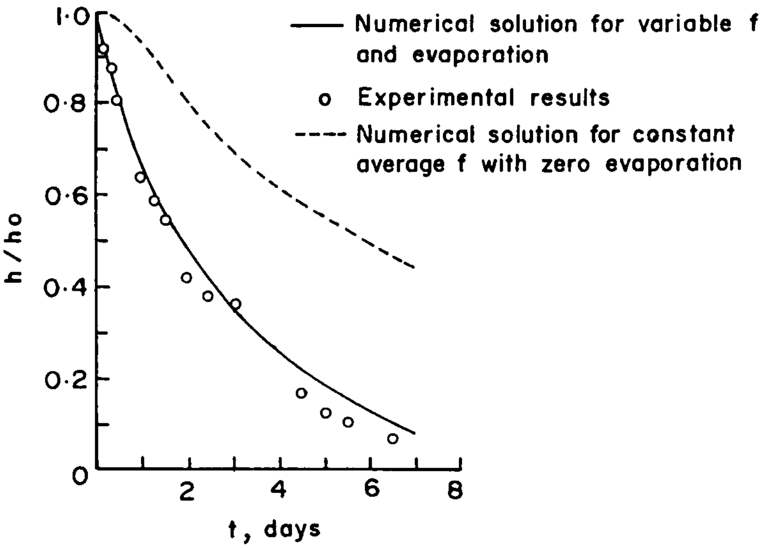

Figure 2. Comparison of observed and predicted hydraulic heads in sand tank model study.

Solution based on Bouwer and van Schilfgaarde approach

The solution proposed on the basis of Bouwer and van Schilfgaarde (1963) is given by eq. (11) and eq. (15). These solutions were extensively tested to evaluate the effect of various parameters and to evaluate the sensitivity of the solution to number of linear segments (Nikam et al. 1992). It has been shown that number of segments as well as the appropriate selection of parameters could influence the results. With appropriate selection of parameters, number of segments can be reduced so that it is easier to manage the solution.

Experimental data from a subsurface drainage system were utilized to verify the validity of the application of the derived solution. The depth to water table at midpoint between the drains as a function of time is plotted in Fig. 3. The predicted curves with eq. (11) and from equation of Bouwer and van Scilfgaarde (1963) are presented with the observed data. It may be seen that transient water table as shown by curves B and C are quite close to the observed field data for about 3 days. Beyond this period, there is increasing mismatch between the curves. The observed depth to water table is higher than the predicted values. Overall curve B described the data better than curve C mainly because in the former variation in the evaporative demand has been accounted for. The mismatch between the observed and predicted values could be on account of many reasons. One of the reasons could be the inappropriate value of constant C which has been taken as a constant while in practice it increases as the depth to water table increases. Secondly, in field situations and particularly in the isolated drainage systems as the one from which this data set has been collected, there is possibility of increased recharge from the adjacent undrained land resulting in relatively slow decline in the water table in the drained land after the initial drawdown.

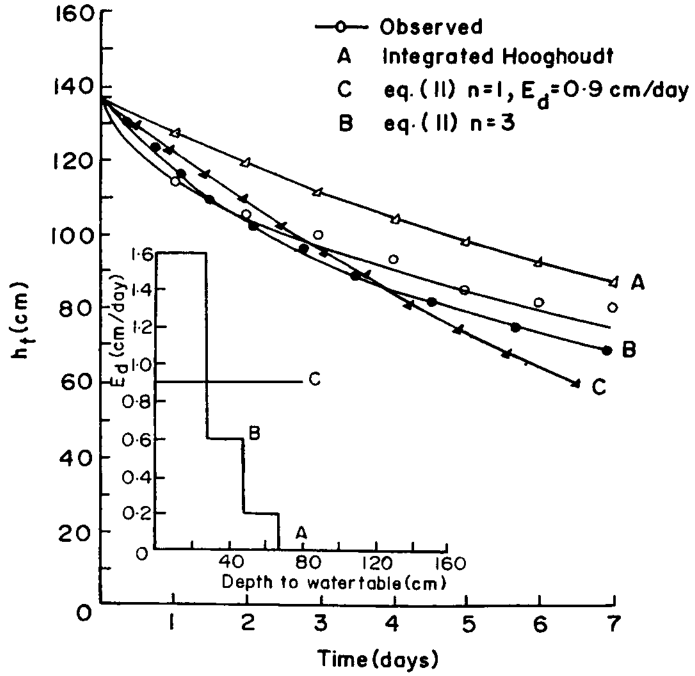

Figure 3. Observed and predicted hydraulic heads for a field study utilizing Eq.(11)

General comments

Evaporation/ET is one of the important process that determines the rate of fall of the water table in a drain or undrained land. Experimental data from subsurface drainage systems in the semi-arid regions are hardly amenable to the existing equations which do not account for the process of evaporation/ET. Out of the 3 proposed solutions, it is difficult to comment upon the relative application of one over the other as each of the solution has its own advantages or disadvantages. While taking a decision as to which of the solutions should be used,it is necessary to consider the relative contribution of evaporation vis-a-vis tile flow. For most accurate description of the evaporation/ET, solution based on piecewise linear model would be desirable. On the other hand for more complex situations as were experienced in the sand tank study, numerical solution may be the only alternative.

Practical applications

Recent investigations in India and elsewhere have conclusively established that drain spacing estimated with the existing equations would be inappropriate as long as actual processes of evaporation and recharge are not accounted for in the design equations (Skaggs, 1975; Gupta, 1985). in order to economize on cost particularly in developing countries where resources are often limited, realistic design equations would be quite useful. The application of the proposed analytical solution in drainage design has been evaluated for some realistic settings of semi-arid region in India. The predicted drain spacings with and without evaporation show an increase up to

25 per cent over and above the design spacing for cases in which evaporation has been neglected (Table 1). Similarly the application of proposed solutions in analysing and interpreting data from drained lands is immense. To some extent such applications of the models have been discussed in previous sections. it is opined that proposed equations would find increasing applications under arid and semi-arid conditions as are prevalent in the Indian sub-continent.

Case	Calculated drain spacing (M)	% increase in drain spacing over case 1
1. No Evaporation/ET	36.00	-
2. Evaporation/ET linearly decreasing	42.50	18
3. Evaporation/ET at constant rate	45.00	25

Table 1. Predicted values of the dimensionless hydraulic head at 2 days time for different drain spacings

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RAINFALL-RUNOFF RELATIONS
IN THE RURAL AREA OF THE FLEVOPOLDERS

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ABSTRACT. Eastern Flevoland is the largest polder of the Zuyderzee reclamation project, in the Netherlands. On four plots in this polder series of hourly data of precipitation, groundwater table and runoff were collected. The plot sizes vary between 30 and 45 ha; three of them are used for arable farming (they differ in soil type, from clayey loam to clay), one for wood production (deciduous forest). The data series cover between 2.5 and 8.5 years, and were collected from 1977 to 1986.

The aims of this research project are:

- to obtain a better understanding of the rainfall-runoff process in reclaimed marine clay soils, which have a very specific character, due to (permanent) cracks;
- to give thoroughly based design criteria for future water management systems in similar soils and under similar climatological conditions.

To explain the measured data series, a Fortran computer model was written, which calculates groundwater tables and discharges per hour with hourly precipitation data and daily potential Penman evaporation data as input. A pseudo-stationary approach is used in the calculations. The effect of cracks is accounted for by assuming a non-linear relation between hydraulic conductivity and water level.

The main results of the research project are:

- the differences in rainfall-runoff relations between the three agricultural plots, as expected because of different soil types, are greatly reduced by the applied subsurface drain distances;
- the actual evapotranspiration of wood is significantly higher than that of agricultural crops, under the circumstances under consideration;
- the resulting design discharge, that is the discharge with a recurrence interval of one day per year, is 15 mm/day for arable farming, and 10 mm/day for wood.

RESUME. *Flevoland de l'Est est le plus grand polder du Projet d'Assèchement de la Mer Zuyderzee, aux Pays-Bas. Sur quatre bassins hydrologiques dans ce polder, la précipitation, le niveau phréatique de la nappe et le débit ont été mesurés. La largeur des bassins est de 30 a 45 ha; trois d'entre eux sont utilisés pour l'agriculture, le quatrième est en forêt.*

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Les buts du projet de recherche sont:

- *d'obtenir une meilleure appréhension du processus de transfert d'eau dans ces sol argileux et fissurés,*
- *de donner des normes d'assainissement pour de pareils sols, sous des conditions climatologiques identiques.*

Un programme en fortran a été écrit pour calculer les débits d'assainissement et hauteurs de nappes à partir de données horaires des précipitations et de données journalières de l'évaporation de Penman. Les principaux résultats du projet de recherche sont:

- *l' évapotranspiration actuelle de la forêt est grande que celle des bassins versants agricoles,*
- *le débit de projet (le débit qui est dépassé un jour par an), est de 15 mm par jour pour les bassins versants agricoles, et de 10 mm par jour pour la forêt.*

INTRODUCTION

Four polders, with a total area of 166,000 ha, have so far been reclaimed in the Zuyderzee project. These polders are drained by a network of subsurface drains, ditches and canals, with the excess water in the canals pumped out via pumping stations. The design rationale for the canals, ditches and pumping stations has an empirical background, based on the long history of land reclamation in the Netherlands (de Jong, 1972).

The soils in the Zuyderzee Project Area, however, have a special quality: they are marine sediments which have never before been exposed to air. When these soils are reclaimed, a series of physical and chemical processes, related to aeration, takes place. These processes are called 'ripening of the soil' (de Glopper, 1969). Soil ripening is a vital factor for water management engineers: it causes irreversible shrinkage, due to water loss from the soil. In vertical direction this shrinkage causes subsidence, in horizontal direction crack formation. The amount of shrinkage is related to the clay content of the soil. The more clay, the more subsidence and crack formation must be expected (De Glopper, 1969; Rijniersce, 1983).

The amount of cracks and the depth to which they are interconnected determine the hydraulic conductivity of the soil. The highest conductivities, therefore, are found in the soils with the highest clay contents. The depth to which the cracks reach is related to the depth to which ripening takes place. This depth is related to the maximum rooting depth of the crops, typically about 1 meter, under trees usually somewhat more. Because the cracks, from the unripened zone upward, gradually increase both in width and in intensity, the hydraulic conductivity increases from the unripened zone upward.

Although these soil properties were known qualitatively for a long time, they had never been investigated thoroughly in the field. To do so, to give a reliable basis to discharge system dimensions and to gain a better general understanding of the rainfall-runoff process in these areas, four representative basins on different soils have been gauged. Of these four, three are arable land (called agr1, agr2 and agr3), and one is planted with popular trees (called wood). With the data collected in these basins a model describing the rainfall-runoff process was calibrated.

DESCRIPTION OF THE RESEARCH BASINS

The research was carried out on four research basins. Three of these basins are in use as arable land, one for wood production. The general characteristics of the four basins are given in table 1.

The four basins were chosen in such a way as to cover the whole range of soils found in the polders. All four basins are drained by subsurface drains. From table 1 one can see, that the drain distance increases with increasing clay content. The surface levels of the basins are well below mean sea level, which is given by the Ordnance Date (OD).

The soils in the Zuyderzee polders generally consist of Holocene layers on top of a Pleistocene sandy subsoil. The Holocene layers have a varying nature; they can consist of sand, loam, peat or clay, and range in thickness from 1 to 10 meter. Depending on the hydraulic head in the subsoil, upward or downward seepage to the Pleistocene sand may take place. On agr3 upward seepage can be detected in the field; in the other basins a downward seepage of about 40 mm per year was calculated.

The discharge of the basins was measured at the basin outlet, i.e. at the end of the farm ditch in which the drains end. Usually the drain ends were well above the ditch water level; this means that the discharge from the drains is not influenced by the ditch water level. On basin wood, however, this was not the case due to poor ditch maintenance.

	agr1	agr2	agr3	wood
land use	arable	arable	arable	wood
soil type above drainlevel	loam	loam	clay	clay
soil type below drainlevel	sand	loam	loam	loam
depth Pleistocene sand (m bss)	2.0	3.0	1.8	2.0
0 % aeration depth (m bss)	1.20	1.30	1.15	1.45
area (ha)	28.8	29.6	29.5	46.5
drain distance (m)	8	24	48	48
mean drain depth (m bss)	1.15	1.10	0.95	1.05
mean surface level (m OD)	-4.30	-4.35	-3.60	-4.30

Table 1. General characteristics of the four research basins.

DATA COLLECTION

The four research basins were equipped with Ott and Microdata data loggers, collecting hourly data of:

- rainfall;
- groundwater levels at two locations;
- pressure head in the underlying aquifer (basin 'wood' only);
- discharge at the basin outlet.

Additional data, such as soil descriptions, physical soil data and moisture content, were collected at regular intervals.

The duration of data collection was not equal on all basins:

- on agr1 from december 1977 to may 1980;
- on agr2 from december 1977 to june 1986;
- on agr3 from december 1977 to may 1980;
- on wood from september 1979 to september 1985.

DESCRIPTION OF THE SIMULATION MODEL

Soil profile schematization

The system that transforms rainfall into discharge consists of the different layers in the soil profile. For sake of convenience, some of the equations governing the water movement are considered as reservoir equations, whereas others are based on stationary flow equations.

The way in which the soil profile has been schematized is depicted in figure 1. Rainfall reaching the vegetation (in summer) subsequently runs through:

- the interception reservoir (free water directly evaporating from the vegetation);
- the ploughed layer;
- the unsaturated, fissured zone;
- the unsaturated, non-fissured zone (if the groundwater level is below the unsaturated, fissured zone);
- the saturated zone;
- the drains and ditch to the basin outlet.

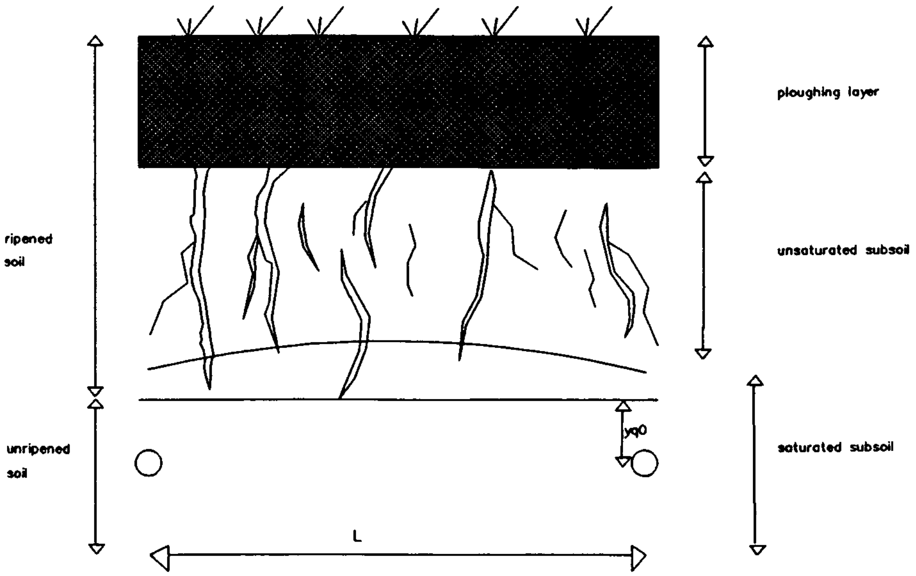

Figure 1. Schematization of the soil profile.

Process description

In the model a pseudo-stationary approach has been adopted. Per time-step of 1 hour a water balance is calculated. The terms of the water balance are: precipitation, evapotranspiration, seepage, discharge and changes in storage.

Potential evapotranspiration is calculated according to the Monteith-Rijtema formula (Monteith, 1965; Rijtema, 1965). The model makes a distinction between interception evaporation, soil evaporation and transpiration.

Interception evaporation depends on the actual storage in the interception reservoir. The content of the interception reservoir is calculated from day to day from a water balance. The maximum storage capacity of this reservoir was taken from (Begeleidingsgroep Gelgam, 1984) (for arable crops) or found by optimisation (for wood). The rate of evaporation from the interception reservoir is equal to the open water evaporation, calculated with the Penman formula (Penman, 1948). Soil evaporation E_{soil} depends on the pF in the root zone and the Penman evaporation E_{Pen}:

$$E_{soil} = \frac{4.2 - pF}{4.2} \cdot E_{pen} \qquad (1)$$

Transpiration is calculated according to Monteith-Rijtema. Root extraction takes place in the upper soil layer, the plough layer (see below), until the readily available moisture is depleted. Then extraction takes place from the layer underneath; when the mean moisture content of this layer reaches a limiting value taken from Van Wijk et al. (1988), root extraction is reduced, and eventually comes to a standstill. In the period of measurements however, a complete standstill never occurred. The maximal rooting depth of the crops was found by optimisation. The increase of the rooting depth during the first stages of crop growth was calculated according to Van Wijk et al. (1988).

Movement of moisture from one soil layer to the other is calculated with stationary flow equations (de Laat, 1980). Per layer one value is calculated for pF, moisture content and hydraulic conductivity. For this purpose pF-curves and unsaturated hydraulic conductivities were measured. Apart from the water movement through the soil columns, water can run through the cracks as bypass flow. This flow will occur, when the water content of the plough layer (into which the cracks do not extend, because they are disturbed) has risen to an optimised value. Above this value, rainfall is supposed to run as free water through the macropores to the cracks underneath. The water movement in the plough layer is calculated from infiltration, capillary and evapotranspiration. Root extraction is mainly situated in this layer. When the water content of the plough layer rises above the value corresponding to pF = 1.8, the nature of water movement changes: water starts to run as free water through the macropores, and reaches the underlying layers quickly.

The water can run through the second layer (the unsaturated, fissured zone) in two ways. The first is percolation (downward) or capillary rise through the soil columns, calculated with the stationary flow equation:

$$Q_{cap} = K_{uns}(h) \cdot (\frac{\Delta h}{\Delta z} - 1) \tag{2}$$

in which

Q_{cap}	: capillary rise, positive upward ($mm \cdot d^{-1}$)
$K_{uns}(h)$	: unsaturated hydraulic conductivity ($mm \cdot d^{-1}$)
Δh	: difference of suction head (cm)
Δz	: level difference (cm)

The second way of moisture transport through the second layer is by short-circuiting through the fissures, along the sides of the soil columns. This process takes place, when the plough layer is wet enough to let (intensive) rainfall pass by as free water. Short-circuiting water is supposed to reach the next zone (either the unsaturated, non-fissured zone or the saturated zone) without delay. When bypass flow is calculated, some of the water running along the sides of the soil columns may infiltrate horizontally into the columns. According to Hoogmoed and Bouma (1980) this quantity is small, because the wetted area of the column sides is limited. From some initial calculations in this research the same conclusion showed; horizontal infiltration was therefore neglected. Root extraction can take place from this layer, when the readily available moisture in the plough layer is depleted.

When percolation occurs, the water content in the third layer (the unsaturated, non-fissured zone) will rise until the whole layer has become saturated. If percolation goes on, the water table reaches the fissured zone, and drainage will start.

For each timestep, the storage in the layers of the unsaturated zone is calculated in an iterative procedure and expressed as a saturation deficit. From these calculations the result is a net percolation (IN, positive) to or capillary rise from the saturated zone (IN, negative); the new value of the storage in the saturated zone SS is then calculated according to (6).

If the groundwater level is higher than the level y_{q0}, the storage in the saturated zone is translated to a groundwater table by a storage coefficient, which is found by optimisation; this storage coefficient reflects the volume of fissures and macropores. If the groundwater level is below the level y_{q0} (i.e. in the non-fissured zone) the groundwater level is calculated from the capillary rise and the storage deficit of this layer SDUC, according to (2).

When the groundwater table rises above a certain level y_{q0}, discharge will start. The level y_{q0} is found from plots of measured discharges against measured groundwater tables. This level characterises the depth in the profile, to which the cracks are interconnected; it is not necessarily equal to drain depth, but is found somewhere between the levels of full and zero aeration.

In principle the discharge could be calculated from the groundwater level by such stationary formulas as the Hooghoudt or Ernst equation (Hooghoudt, 1940; Ernst, 1962), but for the fact that the hydraulic conductivity is strongly dependent on the depth in the profile. In the Hooghoudt formula, stationary discharge is related to the groundwater level as:

$$q = \frac{4\,K\,m^2 + 8\,K\,d\,m}{L^2} \tag{3}$$

with:

q : drain discharge ($m \cdot d^{-1}$)
m : elevation of the groundwater level midway between the drains, with respect to drain level (m)
K : saturated hydraulic conductivity ($m \cdot d^{-1}$)
d : equivalent thickness of the flow domain below drain level, according to Hooghoudt (m)
L : drain distance (m)

As the flow through the unripened layers below drain level can be neglected, due to the low hydraulic conductivity, this formula can be simplified to:

$$q = \frac{4\,K\,m^2}{L^2}$$

So according to Hooghoudt, there is a quadratic relation between discharge and groundwater level, if the hydraulic conductivity is a constant. As hydraulic conductivity depends on the depth as well, this formula does not give an accurate description of the discharge in these fissured soils. Therefore a discharge formula was adopted of the form (Ven, 1979):

$$q = C \, . \, m^N$$

with N and C as parameters to be optimized. With $C = 4K/L^2$ and $N = 2$ this becomes the Hooghoudt formula for flow above drain level. To avoid complicated non-stationary calculations, the storage in the saturated zone SS is then calculated from the average value of the discharges of the same and the preceding timestep (Ven, 1979):

$$q \;=\; SSt - \frac{q_{t+\Delta t} + q_t}{2} \,.\Delta t + (Q_{cap} + Q_{by}) \,.\, \Delta t \qquad (6)$$

in which:

SS_t : saturated storage at timestep t (mm)
q_t : drain discharge at timestep t ($mm \cdot hr$)
Δt : length of timestep = 1 hour
Q_{cap} : percolation (positive upward) ($mm \cdot hr^{-1}$)
Q_{by} : bypass flow ($mm \cdot hr^{-1}$)

With the above formulas the discharge was calculated; to this discharge a term is added to account for upward seepage (basin agr3); if seepage is downward, it is subtracted from the storage in the saturated zone. As the discharge was measured at the basin outlet instead of the drain outlet, a time lag TAU (hr) was thought to be needed to account for the time needed for transport through the drain and ditch. Because the model works in timesteps of one hour, the time lag can only be given integer values. The time lag was found by optimisation to be equal to zero. This means that a change in groundwater level will have its effect on the discharge at the outlet in less than half an hour.

Water ponding and surface runoff are not likely in these flat areas and are therefore not included in the model.

The discharge is only related to the mean groundwater level; the actual shape of the phreatic level between the drains is not taken into account.
Although attempts were made to account for the influence of snowfall and the resulting retardation in discharge response, this process could not be satisfactorily modelled and is not included in the model. The main reason for this is the fact that precipitation data in these periods are unreliable, due to snow blown in from the ground into the rain gauge.

Reversible swelling and shrinkage processes are measurable in these soils (Bronswijk, 1991). The effect of these processes might be a gradual change in hydraulic conductivity. Such an effect, however, cannot be found from the discharge data in the winter periods, and no field data are available to demonstrate the more subtle changes during summer. For these reasons reversible swelling and shrinkage processes are neglected.

Object functions

The program has an option to calculate the optimal values of unknown parameters. A modified version of the Rosenbrock scheme (Clarke, 1973) was used for this purpose.

For the calculation of the goodness of fit between measured and calculated discharges, two so called object functions are used: ISE (Integral Square Error) and the Model Efficiency R^2. The object function ISE was used for the optimization of the parameters. As ISE is dependent on the actual amount of discharge, it cannot be used to compare the results of different basins and/or different calculation periods. For this purpose the Model Efficiency is used. These functions are calculated as follows:

$$ISE = \frac{\sqrt{\sum_{i=1}^{i=n} (q_{obs,i} - q_{mod,i})^2}}{\sum_{i=1}^{i=n} q_{obs,i}} \times 100\ \% \tag{7}$$

with:

n : number of timesteps for which either q_{mod} or q_{obs} or both are higher than zero (-)
$q_{obs,i}$: observed discharge for timestep i (mm·hr^{-1})
$q_{mod,i}$: modelled discharge for timestep i (mm·hr^{-1})

$$R^2 = \frac{\sum_{i=1}^{i=n} (<q>_{obs} - q_{obs,i})^2 - \sum_{i=1}^{i=n} (q_{mod,i} - q_{obs,i})^2}{\sum_{i=1}^{i=n} (<q>_{obs} - q_{obs,i})^2} \tag{8}$$

with $<q>_{obs}$: mean value of discharges if discharge > 0 (mm·h^{-1}).

All timesteps in which both observed and modelled discharge are equal to zero are left out of these calculations. The optimal value of ISE is 0, that of R^2 is 1.

RESULTS

Discharge as calculated from measured groundwater levels

For the calculation of discharge from the measured groundwater levels, a simplified version of the model was used. In this simple version, all steps before the saturated zone are left out; the model does not calculate a water balance, it just relates groundwater levels to discharge, according to [4]. The parameters N, C and TAU are found by optimisation. For these optimisations selected winter periods were used. The results are summarised in table 2.

	TAU (hr)	y_{q0} (m + drain level)	C (-)	N (-)	R^2 (-)
agr1	0	-0.05	6.23	3.51	0.69
agr2	0	0.09/0.19	130.4	3.45	0.93
agr3	0	0.03	737.8	3.33	0.92
wood	0	-0.09/-0.19	311.9	3.89	0.88

Table 2. Optimal parameter values per basin, as an average of the available data series. The data series cover winter periods from december to march.

The relations between discharge q and groundwater level with respect to level y_{q0}, summarised in table 2, are depicted in figure 2. From this figure one can see, that agr1 with its loamy, hardly fissured soil, needs a much higher head to drive the same discharge out of the profile than the other basins.

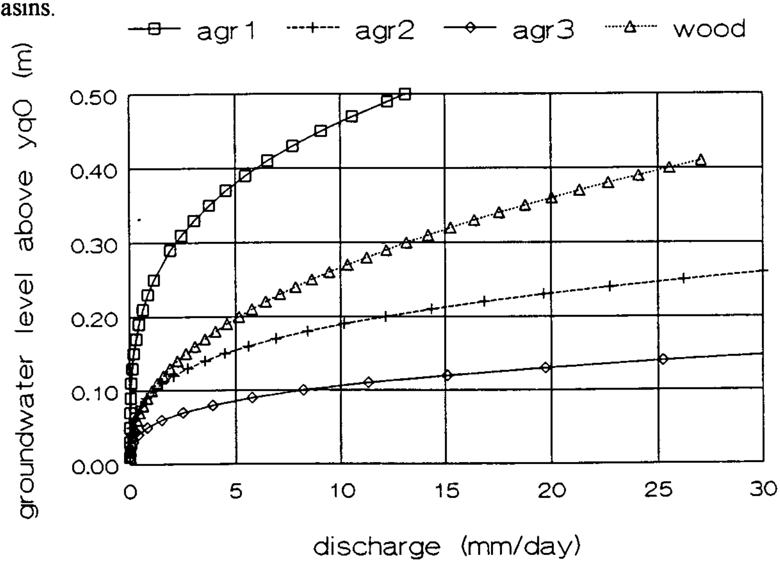

Figure 2. Modelled relations between groundwater level and discharge per basin.

From the relation between discharge and groundwater level and the Hooghoudt formula one can calculate the saturated hydraulic conductivities. The values thus calculated are 1.0 $m \cdot d^{-1}$ for agr1, 60 m·d^{-1} for agr2, 800 m·d^{-1} for agr3 and 300 m·d^{-1} for wood.

The resulting optimal values of the parameters are used in the complete version of the program, which calculates the discharge from precipitation, evapotranspiration, seepage and changes in storage.

Discharge as calculated from the water balance

For the calculation of discharge from water balance data some additional parameters are required, concerning evapotranspiration, the water movement in the unsaturated zone and seepage. An overview is given in table 3. Not included in table 3 are the parameters measured in the field: pF, unsaturated conductivity, soil profile data, harvesting data etc; also the parameters taken from literature for the calculation of the evapotranspiration are left out.

		parameters derived from relation discharge - groundwater level
parameter	units	description and application
TAU	hr	time lag between groundwater suppletion and discharge at the basin outlet
C	-	coefficient in relation groundwater level -discharge
N		coefficient in relation groundwater level -discharge
y_{q0}	m + dr.l.	lowest groundwater level at which discharge occurs
		additional optimised parameters
parameter	units	description and application
SIM	mm	max. capacity interception reservoir
SDUA1	mm	initial storage deficit of the plough layer
SDUB1	mm	initial storage deficit of the unsaturated fissured zone
SDUC1	mm	initial storage deficit of the unsaturated non-fissured zone
SS1	mm	initial storage saturated zone
SEEP	mm·d^{-1}	seepage to (neg.) or from (pos.) Pleistocene aquifer
MU	-	storage coefficient of the saturated, fissured zone
MDRZ	m	maximum depth of the root zone

Table 3. Parameters in the model.

Calculations were performed per year from April to March, optimising the parameters. The values of the parameters found were averaged, except the initial storages and the values of y_{q0}. An overview of all parameters and their values for each basin are given in table 4.

parameter	agr1	agr2	agr3	wood
TAU (hr)	0	0	0	0
y_{a0} (m+dr)	-0.05	0.09/0.15	0.03	-0.09/-0.19
C (-)	6.23	130.4	737.8	311.9
N (-)	3.51	3.45	3.33	3.89
SIM (mm)	1.0	1.0	1.0	3.5
SDUA1 (mm)	variable	variable	variable	variable
SDUB1 (mm)	variable	variable	variable	variable
SDUC1 (mm)	0	0	0	0
SS1 (mm)	variable	variable	variable	variable
SEEP ($mm \cdot d^{-1}$)	0.0	-0.1	0.4	-0.15
MU (-)	0.040	0.069	0.18	0.154
MDRZ (m)	0.60/0.80	0.60/0.80	0.60/0.80	1.00
average R^2_v	0.55	0.72	0.75	0.80
average R^2	0.72	0.75	0.85	0.88

Table 4. Overview of parameter values for each basin, and average values of the object functions R^2 and R^2_y.

The quality of the results is illustrated in figures 3 and 4. In these figures, the results of agr2, 1980/1981, and wood, 1980/1981, are plotted. For agr2, R^2 is 0.75 and R^2_y is 0.72; for wood, R^2 is 0.92 and R^2_y is 0.89.

Groundwater levels as calculated from the water balance

As shown in figures 3 and 4, the model calculates the groundwater levels fairly accurately, although the reaction to rainfall in midsummer is not always correctly predicted. As the groundwater levels on agr1, agr2 and agr3 were only measured under one crop, the values of R^2_y only refer to the crop that was grown. The values of R^2 however refer to average values of all crops grown. Because of this, the model efficiencies of the groundwater levels are usually lower then those of the discharge.

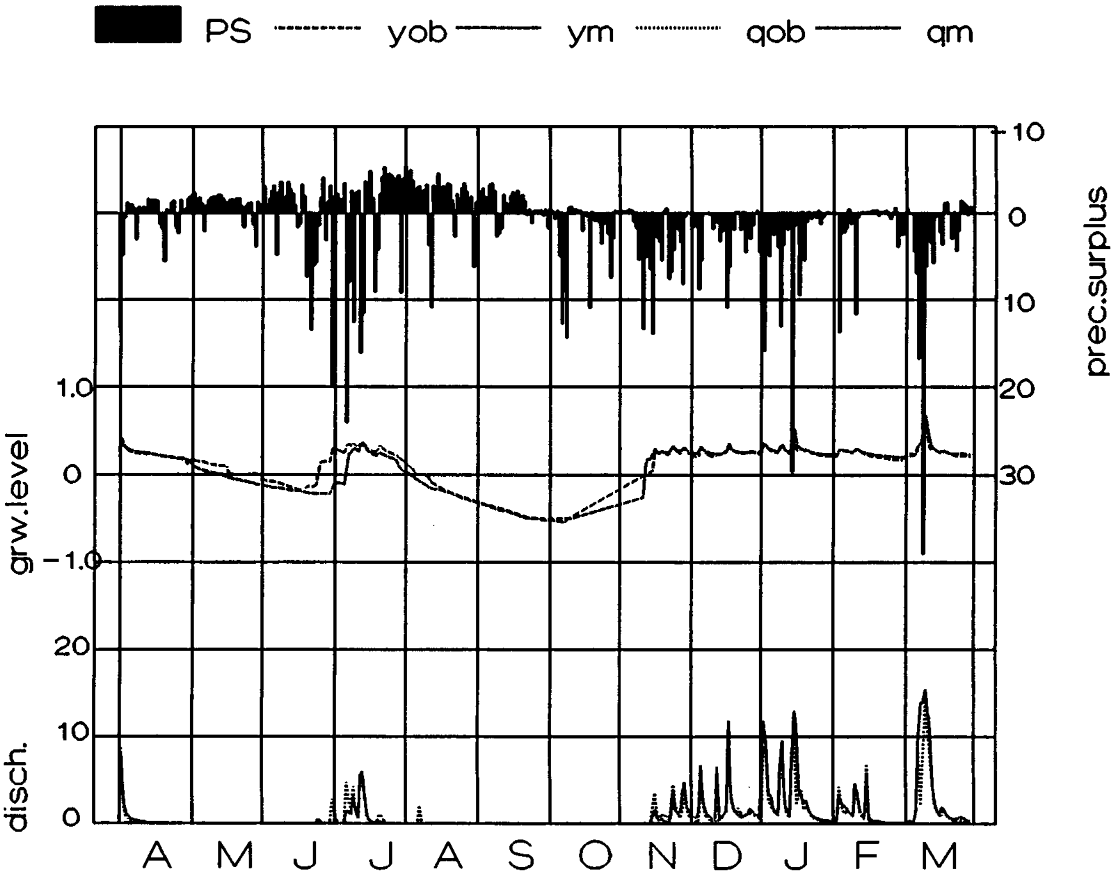

Figure 3. Calculated precipitation surplus (PS, in mm), observed and modelled groundwater level (yo, ym, in m above drain level), observed and modelled discharge (qm, qo, in mm per day); basin agr2, april 1980 to march 1981.

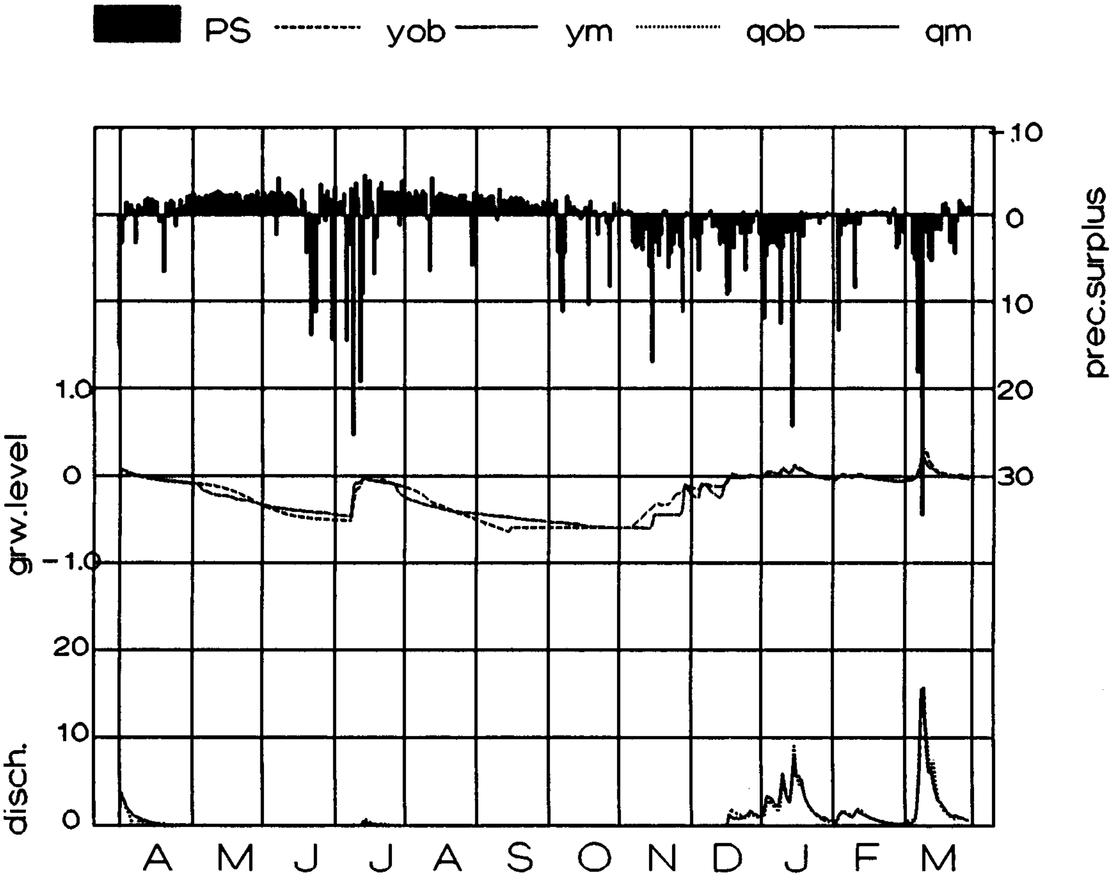

Figure 4. Calculated precipitation surplus (PS, in mm), observed and modelled groundwater level (yo, ym, in m above drain level), observed and modelled discharge (qm, qo, in mm per day); basin wood, april 1980 to march 1981

APPLICATIONS OF THE RESULTS

Frequencies of extreme discharge intensities

One of the aims of the research is to check the validity of the design discharge. The design discharge is defined as the discharge in mm per day that will be reached or exceeded during one day per year. So far, the applied value was 13 $mm \cdot d^{-1}$, or 1.5 $l \cdot s^{-1} \cdot ha^{-1}$.

The observed and calculated discharge data were ranked in classes of 2.5 mm, and the exceedance frequency in day per year calculated. This was only done for plots agr2 and wood, as in these basins the longest data series are available. The results were plotted; from the resulting regression lines, the discharges with exceedance frequencies of 0.1, 1.0 and 10 days per year were calculated. These discharges are given in table 5.

exceedance frequency (day per year)	0.1	1.0	10
design discharge (mm per day)			
agr2	23.0	15.2	7.4
wood	16.1	10.4	5.7

Table 5. Exceedance frequencies and corresponding discharges as calculated for basins agr2 and wood.

Modelling the discharge of a polder

The research basins all lie in the same polder unit of the Flevopolder. The area of this polder unit is 57,000 ha, 72 % of which is agricultural land, 15 % wood, 10 % urban area and 3 % nature reserve.

The polder unit is kept dry by three pumping stations, which together can remove a layer of 11 mm water per day. From the Water Board, daily amounts of pumped out water were obtained, and compared with the discharge data of this research. As expected, an additional seepage term is needed to obtain a fitting water balance. This upward seepage comes from the underlying Pleistocene aquifer, and adds to the water in the larger canals, which are deep enough to cut into the aquifer. This seepage therefore was not found in the shallow ditches of the research basins. With an average seepage of 1.0 $mm \cdot d^{-1}$ the water balances could be made to match. The values of R^2 range from 0.80 to 0.89.

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DRAINAGE MODELS TO PREDICT SOIL WATER REGIMES IN DRAINED SOILS

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ABSTRACT. Drainage is an intervention in the natural hydrology of the soil to alter the duration of adverse (waterlogged) soil conditions. The effects of drainage can be investigated by models that predict the position of the water table at a site in the presence of drainage. An inter-related series of models, which include the van Schilfgaarde non-steady state model, that have been used in the UK for the evaluation of drainage design options, are described. A simplified form of the van Schilfgaarde equation is presented, equivalent to a standard time series model, allowing both the efficient implementation of the model, and the inverse use of the model to derive performance parameters from observational data using statistical methods. A sensitivity analysis is used to investigate the relative importance of the two soil parameters, drainable porosity and soil hydraulic conductivity, on the performance of the model. This shows a far greater effect due to the variation of hydraulic conductivity.

The use of a similar model to predict water tables in non-homogenous soils has also been explored, including the investigation of a two-phase model to describe water movement in soils which are dominated by macropores. More useful, however, is the prediction of water table fluctuations in soils in which the soil hydraulic conductivity is a continuous function of soil depth, using the drainage theory of Youngs (1965). Solutions are presented for the logarithm of the hydraulic conductivity varying linearly with depth. The improvement in model performance is however gained at the expense of an additional parameter that describes the variation of hydraulic conductivity with depth. Some methods for deriving this parameter are discussed. Results from the use of this model are compared with those derived from the simple uniform conductivity model, showing superior performance.

Lastly, the issue of soil lateral heterogeneity and the replicability of measurements is discussed. A detailed study of the variation of water table levels from a replicated drainage experiment indicates that in a practical situation very real limits exist on the accurate measurement of water tables, and that these present limits on our ability to verify models.

RESUME. *Le drainage est une intervention dans l'hydrologie naturelle du sol, dans le but de modifier la durée des conditions défavorables dans le sol (saturation). On peut étudier les effets du drainage avec des modèles servant à prévoir la position de la nappe phréatique dans un site en cas de drainage. Une série de modèles interdépendants, notamment le modèle en régime transitoire de van Schilfgaarde, a été utilisée au Royaume-Uni pour évaluer des options de systèmes de drainage; elle est décrite dans ce document. Une forme simplifiée de l'équation de van Schilfgaarde y est présentée; elle correspond à un modèle de série chronologique standard, et permet la mise en application efficace du modèle ainsi que l'utilisation inversée de celui-ci pour définir les paramètres optimaux, à partir de données observées et en se servant de*

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méthodes statistiques. Il est fait appel à une analyse de sensibilité pour examiner l'importance relative de deux paramètres du sol - la porosité de drainage et la conductivité hydraulique - sur les performances du modèle. Celle-ci révèle que l'effet dû à la variation de la conductivité hydraulique est beaucoup plus important.

On a également étudié l'utilisation d'un modèle similaire pour prévoir la position des nappes phréatiques dans des sols non homogènes, en travaillant notamment sur un modèle à deux phases pour décrire les mouvements de l'eau dans des sols où domine la macroporosité. Il est toutefois plus utile de prévoir les variations de la nappe phréatique dans des sols où la conductivité hydraulique est une fonction continue de la profondeur du sol, en utilisant la théorie du drainage de Youngs (1965). Des solutions sont présentées pour le logarithme de la conductivité hydraulique, qui varie inversement à la profondeur. Cependant, l'amélioration des performances du modèle s'obtient aux dépens d'un paramètre additionnel décrivant la variation de la conductivité hydraulique en fonction de la profondeur. On discute certaines méthodes qui permettent de définir ce paramètre. On compare les résultats obtenus avec ce modèle aux résultats dérivés du modèle de conductivité uniforme simple, et l'on constate que ses performances sont supérieures.

Enfin, on aborde la question de l'hétérogénéité latérale du sol et de la répétabilité des mesures. Une étude détaillée des variations de niveau de la nappe phréatique, à partir d'une expérience de drainage répétée, révèle qu'en pratique, des limites bien réelles existent au niveau de la mesure précise des nappes phréatiques, et qu'elles limitent alors notre capacité à vérifier les modèles.

INTRODUCTION

The use of models

Drainage is an intervention in the natural hydrology of the soil to alter the duration of adverse (waterlogged) soil conditions. The effects of drainage can thus be investigated by models that predict the soil water regime of a site in the presence of drainage. Models thus offer two major functions:

- They indicate the effects of the drainage, both on the agricultural operations of the drained area, and on the recipient environment;
- They indicate the relative effectiveness of drainage design options, and so permit the identification of an "optimal" drainage design.

In practice, however, models for drainage design have not been much used in the UK. Despite the enormous amount of drainage undertaken in the decade 1970-80 (as much as 100,000 ha/year, Robinson & Armstrong, 1988), the average size of each drainage scheme remained small (less than 10 ha), and the costs of each scheme were low (Armstrong 1980). Consequently, the financial resources were not available for extensive soil physical investigations required to determine site parameter values. The fact that a very large area was drained successfully was a tribute to the skill of the drainage practitioners who used their extensive local knowledge and experience to design drainage schemes successfully.

Nevertheless, drainage models have been developed as research tools, and have been used to examine both the range of options available to a new situation, and the potential impacts of drainage schemes on the wider environment. A range of models was developed at the Field Drainage Experimental Unit (now incorporated within the ADAS Soil & Water Research Centre) as part of the Ministry of Agriculture Fisheries & Food support to the agricultural industry. More recently however, the emphasis has been on the identification of environmental impacts of agriculture, and the use of the same models to identify potentials for contaminant movement and to assist in the management of wetland areas for environmental aims.

DRAINAGE DESIGN

Initial work in the 1960s was concerned primarily with the practical issues of the design of drainage schemes. The theoretical soil physical basis had been established, and the Hooghoudt drainage equation was accepted as an adequate tool for "scientific" drainage design. Interest then centred on the estimation of the necessary parameters. Detailed examination of the meteorological data led to the publication of a regional analysis of the rainfall records, and the publication of design rainfall rates for a series of "agroclimatic regions" (Smith & Trafford 1976).

Parallel with this work, detailed study of soils led first to the development of drainage guidelines related to soil properties. The use of soil information was developed by the identification of appropriate design spacings for individual soil series (Rands 1973) which could in some circumstances be extended to the mapping of drainage criteria (Trafford 1975).

Such methods have proved to be entirely adequate for the practical design of small drainage systems, following the techniques documented by Castle et al (1984). Development of drainage models has thus been largely restricted to the research environment. Consequently, they have not been developed into user-friendly packages, but have remained as computer programs that were used by modellers as consultants to specific problems.

NON-STEADY STATE MODELS

The van Schilfgaarde (1965) model was identified as being appropriate for the prediction of the duration of waterlogging in drained soils. This analysis predicts the water table response to a series of recharge events:

$$Mt = A / f(e^{1/A} - 1)\sum_{t=1}^{T} P_t e^{(-T-t+1)/A} \qquad (1)$$

Where

M_t is the elevation of the water table above drain depth at time t,
A is a system defining constant with dimensions of time given by:

$$A = (Fcsf) / K \qquad (2)$$

f is the specific yield (dos Santos Junior & Youngs 1969), normally approximated by the drainable porosity,
F is a geometric shape factor developed by Toksöz & Kirkham (1961):

$$F = \frac{1}{\pi}\left\{\ln s / \pi r + \sum_{n=1}^{\infty}\frac{1}{n}(\cos 2\pi r / s - \cos \pi n)(\coth 2\pi n d / s - 1)\right\} \qquad (3)$$

r is the drain radius
s is the drain spacing,
D is the effective soil depth between the drain and the impermeable barrier. This is calculated from the actual depth modified according to the methods of Hooghoudt, and calculated from the equation in ILRI (1973).
K is the hydraulic conductivity of the soil
c is a correction factor, with a value 0.9 according to van Schilfgaarde, and
P_t is the water table recharge at time t. Normally this is either direct precipitation or effective precipitation (rainfall minus evapotranspiration).

Results from this model can be shown graphically as a sequence of water levels in response to precipitation inputs (Figure 1). Armstrong et al (1980) have shown that this model fits data observed on drainage experiments in the UK. They also demonstrate that this model could be used for the evaluation of drainage design, by examining the duration of waterlogging. The sensitivity of this model to the input parameters was also examined. In a given situation, the parameters of the drainage system are usually well defined, and the uncertainty centres on the values of the soil physical parameters the drainable porosity and the hydraulic conductivity. Varying both these parameters in a systematic manner, and then plotting the sum of squared differences between the observed and predicted water tables (Figure 2) shows that the model is only moderately sensitive to values of the drainable porosity compared to the values of the hydraulic conductivity. Although this observation has been repeated for several sites, it should also be noted that Youngs et al (1991) have found the reverse, that for some situations, the drainable porosity is the more sensitive parameter.

Although the van Schilfgaarde model has proved adequate for general evaluation work, it has also proved to have to several shortcomings, and these have led to the parallel development of alternative models.

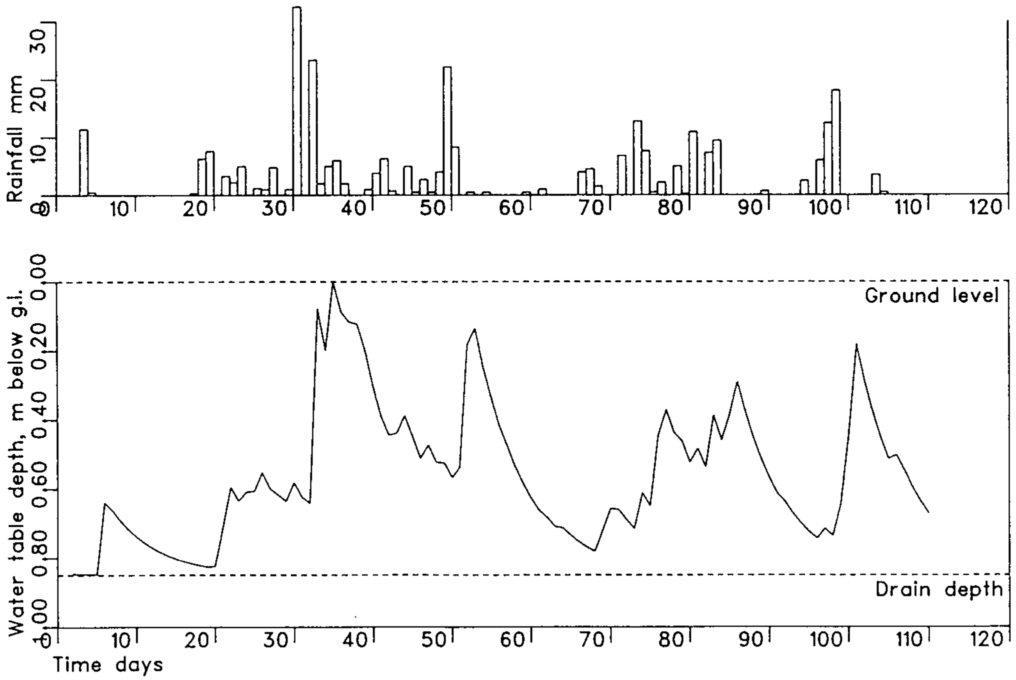

Figure 1. Example output from the van Schilfgaarde model, equation (1). Rainfall and water tables. Soil properties are : Ksat = 0.3 m/day, porosity = 0.05; Drainage system parameters : spacing 20m, depth 0.85 m, pipe radius 40 mm

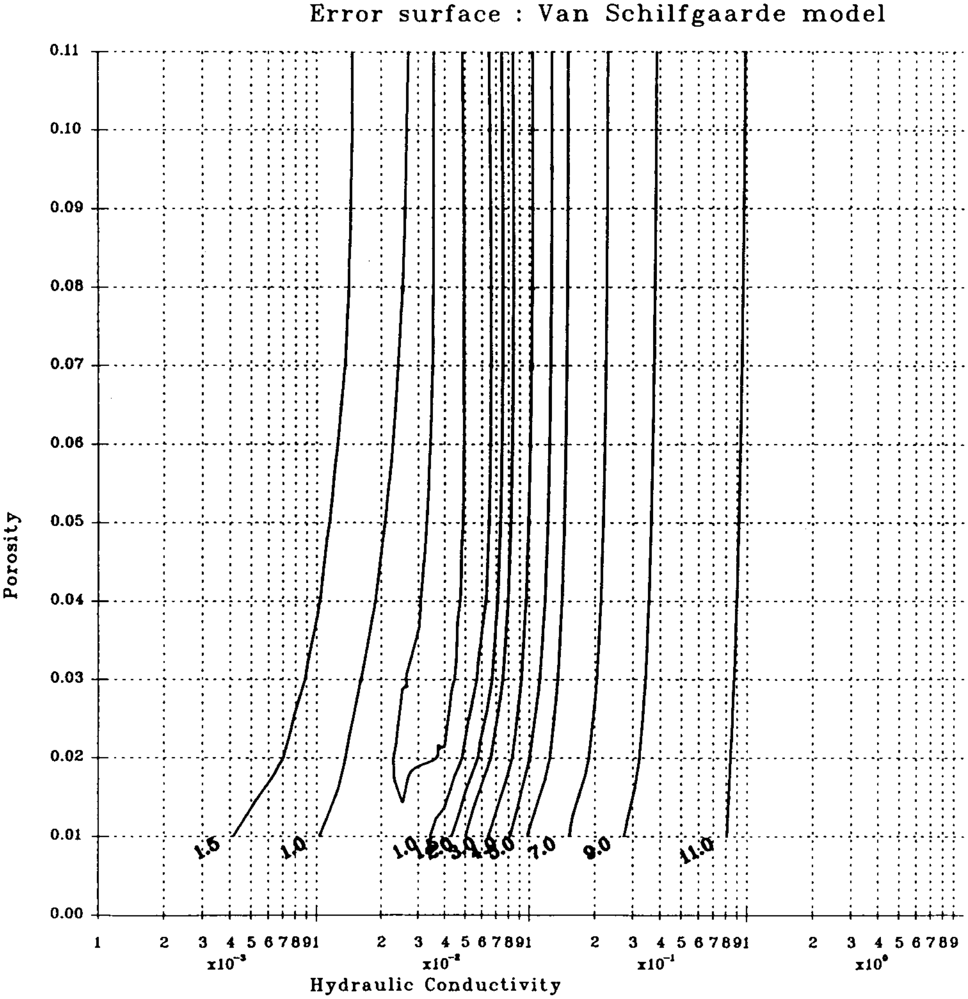

Figure 2. Example sensitivity diagram for the van Schilfgaarde model. The sum of squared errors between observed and predicted water tables is plotted as a function of hydraulic conductivity and drainable porosity

MODEL SIMPLIFICATION

As defined at (1) above, the van Schilfgaarde equation involves much repetitive calculation, which can make even computer implementations of the model slow. Fortunately the infinite sum for the Kirkham F, (3), need be calculated only once for a given set of drainage parameters, and converges rapidly. However, the sum on the right hand side of the equation can soon involve a large amount of calculation, particularly when using small time steps, as the equation has a "memory" always going back to the start of the modelled period. However, examination of the equation shows that the summation recalculates the time of history of the whole model. Armstrong (1987) has shown that by defining two new parameters:

$$\beta = e^{(-1/A)} \tag{4}$$

and

$$\alpha = (A/f)(1-\beta) \tag{5}$$

the model can be rewritten in a much more efficient form:

$$M_t = \alpha P_t + \beta M_{t-1} \tag{6}$$

The model is thus seen to represent the effect of two processes only: the decline of the previous water table from the previous time step, and the effect of the recharge on the time step modelled. This form has been adopted wherever possible, since it offers speed in calculation. With this representation, it is also possible to use small time steps and calculate over long periods without undue performance penalty for the model.

It is also noted that the form of equation (6) is similar to a standard stochastic model, if a single error term is added. Consequently, it is possible to use standard stochastic models to estimate the parameters α and β from any record of simultaneous measurement of rainfall and water table. Using data that had been previously shown to fit the van Schilfgaarde model, Armstrong (1987) showed excellent agreement for the two parameters back-calculated from the stochastic model and calculated from the observed soil physical parameters.

It was also noted that the same model can be used to give estimates of the flux of water through the drains from:

$$Q_t = f(M_{t-1} - M_t + R_t) \tag{7}$$

The model can thus predict the form of a drainage hydrograph, or the flux through the drainage system, as was done by Armstrong & Rao (1987) when considering the use of the same analysis for monsoon conditions. In these circumstances, it was important to know the total flux, in order to predict the solute balance, and so design a system that both gave effective drainage and offered control of salinity.

NON-UNIFORM SOILS

Underlying the van Schilfgaarde equation (1) is the assumption that the soil has homogenous hydraulic properties. This is of course never the case, but is often accepted as an approximation sufficient for most drainage design purposes. However, there are circumstances where this is not adequate. An example was noted when attempting to fit the model to data gathered from the Cockle Park drainage experiment (Armstrong 1984). For this site, the best attempts to model the water table using field measured soil parameters did not match the observed water table behaviour. Equally, optimising the fit of the model by examining the response surface did not materially improve the model performance. There was clearly a mis-match between model assumptions and the real situations, and this was identified as due to the vertical variation in hydraulic conductivity. Field observations had suggested that the hydraulic conductivity decreased with depth, and roughly followed the exponential decline in conductivity observed by Youngs & Goss (1988).

If this description is followed, then it becomes possible to use the results derived by Youngs (1965) for such non-homogenous soils, based on the analysis of the Girinsky seepage potential. For soils in which the variation in hydraulic conductivity is described by the equation

$$K(z) = K_0 e^{\beta z} \qquad (8)$$

where K(z) is the hydraulic conductivity at height z above the drain,
and β is a parameter.

The flux through the drains can be approximated by

$$Q = 2K_0 \, [\{e^{\beta M} - 1\} / \beta D - (M/D)] / \beta D \qquad (9)$$

where D is the half drain spacing (s/2 in the previous notation.)
The sequence of water tables is thus given by:

$$M_t = M_{t-1} + Q / f \qquad (10)$$

Armstrong et al (1991) showed that the parameters K_0 and β can be estimated from field data using simple linear regression techniques, and that the resultant fit for the water table reproduced the observed behaviour excellently (Figure 3).

However, some soils, particularly clay soils, can also be heterogeneous by virtue of containing cracks and other routes for rapid water movement, normally described as macropores. Prediction of water table movement in macropore soils is difficult, and has been the subject of much model development. In practice, the effect of macroporosity can be described as an increase of hydraulic conductivity. The apparent increase in hydraulic conductivity at the surface at Cockle Park, and the success of the variable conductivity model, was most probably due to an increase in soil macroporosity close to the surface.

Nevertheless, the explicit modelling of macropore flow is sometimes required for theoretical studies, particularly where the consideration of solute movement is important. Armstrong (1983) showed how the simple van Schilfgaarde model could be adapted to model two independent phases of flow. Although this model showed a rough agreement with observed patterns of soil water regime (Armstrong & Arrowsmith 1986) it merely confirmed that the two-phase conceptualisation of soil water movement was helpful, and it was left for Jarvis & Leeds-Harrison (1987 a&b) to develop a full and acceptable model of water movement in cracking clay soils. Their model, CRACK, and its later development, MACRO, (Jarvis 1991) has however, remained a research tool.

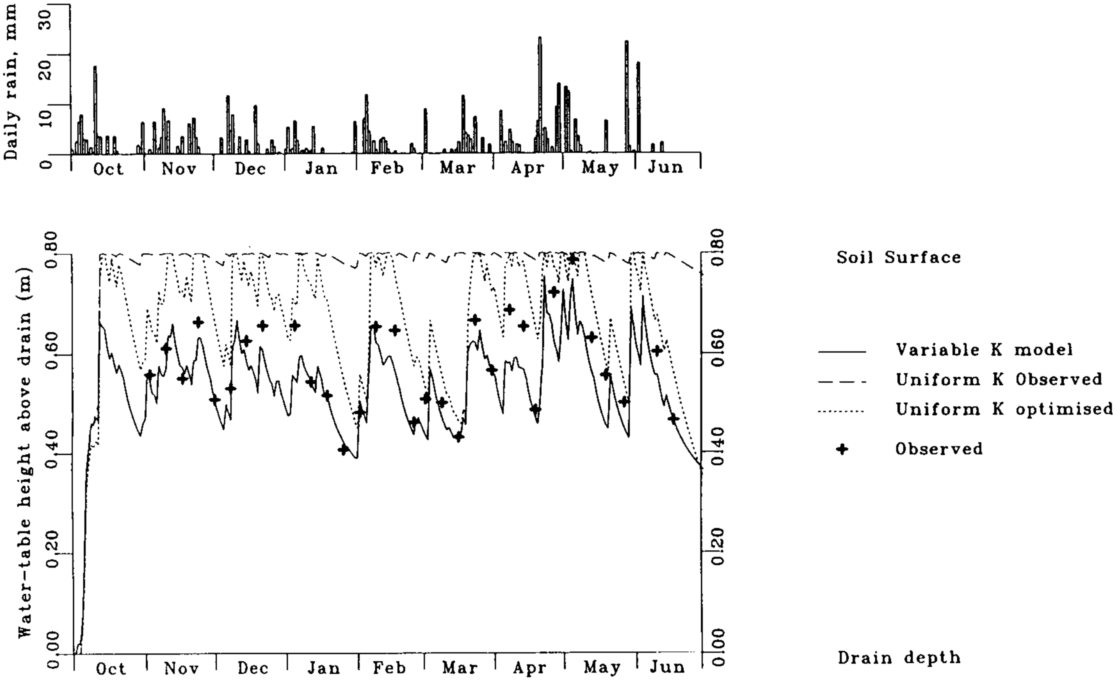

Figure 3. **Rainfall data and model responses for the Wowkle Park drainage experiment, for the winter 1980-91. Observed mean water tables are shown, together with the predictions from the van Schilfgaarde model using the observed K_{sat}, the optimised value for K_{sat}, and the predictions from the variable K model.**

DISCUSSION

The models described above have demonstrated that it is possible to predict the soil water regime in a drained soil. By choice of the appropriate model, reasonable predictions can be made, and the consequences of various design alternatives evaluated.

However models are always limited by the data they require. The issue of soil heterogeneity in the vertical dimension has been discussed, but there is also the problem of soil lateral variability. This issue has been discussed at some length by hydrologists, but has yet to be incorporated into drainage design procedures.

There remains the issue of the accuracy of the measurements that are used to describe the models. The measurement of soil hydraulic conductivity is notoriously difficult, and it is by no means clear that the variability of results is due to soil lateral heterogeneity or due to method itself. Traditionally, the use of mean, or more commonly geometric mean, values is used to provide sensible values for input into design models.

The same issue of accuracy of measurements is raised by the field observations that are used for model development and validation. It is often assumed that the soil water regime can be identified and measured unambiguously, but this may in fact be far from the case. Duplicated measurements of the water table depth will show significant variation between them, even when located close together. For this reason it is normal to consider the mean value of a number of measurements, particularly when using simple unlined auger holes ("dipwells"). Armstrong (1983) has shown that with multiple dipwells, acceptably precise estimate of the means can be obtained. However, even after removing this variability, a variation between replicated plots still remains, such as illustrated by Figure 4 (after Armstrong 1987), which shows the mean water table levels in 6 replicated drainage plots on the North Wyke drainage experiment (Armstrong & Garwood 1991). These represent careful measurement on carefully replicated plots on a soil that was considered to be uniform. Nevertheless, despite the best effort to ensure uniformity of drainage status, and the use of multiple dipwells on each plot to remove scatter, there still remains considerable variation between the plots. There seems to be a residual variation between plots that is probably as large as the residual variation within a plot. It is suggested that this residual variation imposes very real limits on the ability of models to reproduce the soil water regime. By their very simplicity, models fail to reproduce the primary feature of water table data, which is its inherent variability.

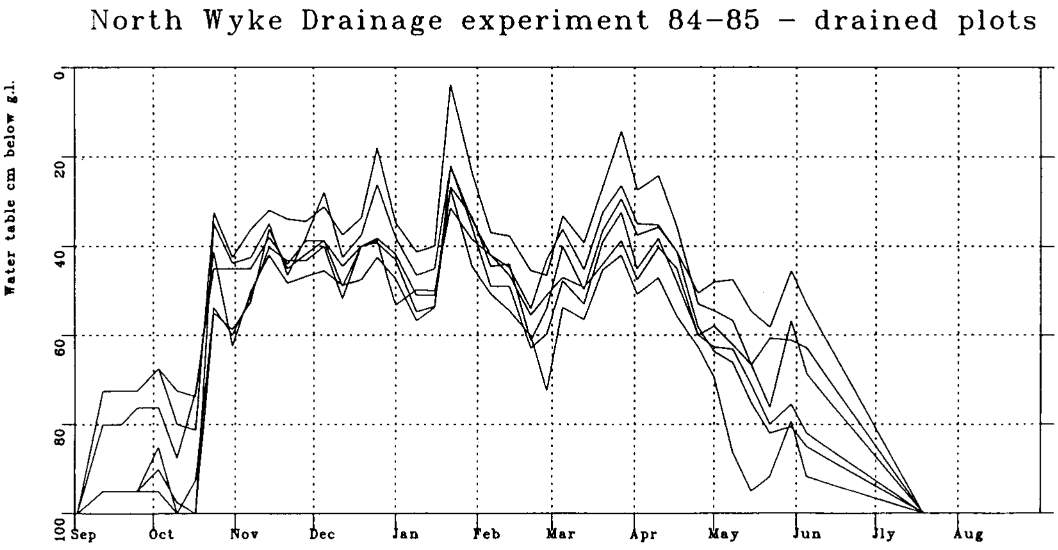

Figure 4. Water tables from the North Wike drainage experiment. Each line is the mean of four replicate dipwells in each of six replicate plots

ACKNOWLEDGEMENTS

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SPREADSHEET PROGRAMME FOR DRAINAGE SYSTEM DESIGN AND EVALUATION

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ABSTRACT. To achieve a proper drainage system design, the water table between drains has to be maintained at a favorable depth. The available field data, the existing field conditions, and the economical situation are the major factors affecting the drainage desing procedure. Therefore, an interactive spreadsheet progarmme, including different design approaches, has been developed. The programme includes a menu bar and pull down menus for the selection of desired formula for drainage design. Options for a comparison between different formulas within the design approach are available.

Sensitivity analysis for each input parameter could be conducted to evaluate the effect of such a parameter on the drainage design. Some practical examples of different approaches have been included. An economical evaluation based on the drainage intensity and the reaction of the water table drawdown and its effect on the soil moisture deficit condition resulting from a certain design choice can be made.

RESUME. *Programme sur tableur pour le dimensionnement et l'évaluation du dimensionnement des systêmes de drainage.*

Pour obtenir un systême de drainage performant, il est nécessaire de maintenir à une certaine profondeur le niveau de la nappe entre les drains. Les dates disponibles, les conditions de terrain existantes et la situation économique sont les facteurs majeurs influençant la procédure de dimensionnement du systême de drainage. Une feuille de calcul a été développée; elle permet de tester différentes méthodes de dimensionnement. Le programme contient une barre de menus et des menus déroulants pour sélectionner l'équation choisie pour effectuer le dimensionnement. On peut à partir de ce programme comparer differentes options.

INTRODUCTION

The ultimate objective of agricultural land drainage is to increase crop yield in a given area. This requirement can be realized by planning a water management system, in which drainage is a component in such a way that the different groundwater table control objectives are maintained, i.e., in humed areas, delay in planting days or stress due to excessive wet or dry soil conditions are constraints to crop production. In arid regions, soil salinity caused by shallow water tables is the main limiting factor. The contamination of drainage outflows by agricultural chemicals imposes additional constraints of planning the drainage system. An optimum design will be the one which leads to maximum crop yield under the conbined effect of these constraints (Skaggs and Trabizi, 1983).

An equally important requirement in drainage system design, is to avoid deficient soil water or

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drought conditions. Dry days are defined as those days in which crop evapotranspiration is limited by soil water conditions (Skaggs, 1978). When water table is drawn down too deep, the ET demand can not only longer be sustained by upward movement alone and the root zone will be depleted. Although droughtness can cause a reduction in yields, most crops have one or more critical periods during which the effect will be more determental than during other periods. The crop response to defecient soil water can be similarly calculated using a stress day index for drought conditions (Shaw, 1978), On the other hand, drainage water quantity is governed by the drain depth. The salinity of drainage water increases with the drain depth, irrespective of the irrigation water quality. Due to heavy nitrogen fertilisers applications, the nitrate concentrations is higher with deep subsurface drainage than with shalow water table. The disposal of saline drainage water or reusing such drainage water containing a high concentration of dissolved salts and toxic levels of agricultural chemicals may casue serious economic and environmental problems. Thus, special attention should be made to the design and opeation of the drainage system. The main objective of the presented paper, is to introduce a user friendly interface to spreadsheet drainage design package. This application interface may be used by decision making in drainage planning and design also be used as eductional tools to understand the drainage system design procedures.

FACTORS AFFECT ON DRAINAGE DESIGN CRITERA

The drainage criteria for the design of the drainage system are usually formulated based on the previlling field condition. For steady state condition, the relationship between a certain drainage coefficient and water table depth is considered the drainage criterion. This relationship may be written as:

$$\frac{h}{q}=\frac{L^2}{8KD} \qquad (1)$$

where,

KD stands for the soil medium, characterized by hydraulic conductivity, thickness, and position relative to drain level of the various layers discerned,

h/q stands for the chosen combination of groundwater level and drain discharge required to prevent the occurrence of excess water in the root zone.

For unsteady state groundwater conditions, the drainage criteria are formulated in term of a required rate at which groundwater table must be lowered. This can be seen by writing the modified Glover-Dumm drainage equation as:

$$L^2=\pi^2\frac{Kd}{\mu}\frac{t}{Ln(1.16h_o/h_t)} \qquad (2)$$

where,

kd/μ : characterised the soil medium,

$t/Ln(1.16\ h_o/h_t)$: stands for the drainage criterion for unsteady stategroundwater conditions.

The symbol (h) in drainage formula, always referes to the groundwater elevation relative to drain level (available head, while the critical groundwater depth is defined relative to ground surface. The drain level therefore must implicity be taken into account when criterion is chosen.

The appropriate choice of drainage criterion will depend on the following set of conditions;

- hydrological conditions, which determined the quantity of excess water to be drained within a specific time;

- agronomic conditions, which depending on the crops and specifics soil conditions, determined the permissible upper limit of the root zones soil moisture content and its duration;

- soil conditions, which determine the relations between aeration and moisture content, groundwater level and soil moisture content, and groundwater level and capillary rise;

- economic conditions, which determined the cost-beneft ratio, i.e., the ratio between the cost of installing a drainage system and the benefits derived from less frequant and less serve yield depressions.

The complexity of the interrelation between all these conditions means that a drainage creterion should be regarded as no more than an attempt to express the aims of drainage system in a single value e.g. h/q, which can be handled mathematically.

ASPECTS OF SUBSURFACE DRAINAGE SYSTEM DESIGN

The subsurface drainage system design procedure have been refered to by (Amer, 1990), as follows:

- the required water table depth to be maintained;
- the required water regime;
- the depth of desalinization;
- the spacing between drains;
- the required transport capacity of collector drains;
- the need of filter or cover envelope around the laterals;
- the auxilary hydraulic structures (manholes, outlets, ..., etc.)

The water table positions that a drainage system should achieve for meeting certain specified water management requirement is primarily related to soil type, climate, crop types and cropping intensity. A water table depth of 0.8-1.0m is being successfully used in the Nile Delta where the crop intensity is in excess of 200% (Abdel-Dayem and Ritzema, 1990). Within the presented package, this criterion have been used but users can update these parameters according to the existing conditions, which maintain an adequate moisture content in rootzone during the dry season and adequate control to the excess water during the wet season. In general, the type of crop determines the depth of the root zone and consequently the drain depth.

The design drainage coefficient (q) is the volume per unit time per unit which determine the removal of water at the required water table depth to obtain the desired crop production. Well establish procedures are known for determining the drainage coefficient humid and arid regions. However the situation in semi-arid zone required more careful analysis (Smedema and Rycroft, 1983).

In general, assuming a steady state conditions, the drainage coefficient may be estimated from the groundwater balance equation or from the total field irrigation losses based on the gross quantity of irrigation water supplied to the field (Amer, 1990). In semi-arid and arid areas, drainage coefficients are likely to be within the range between 1.5 mm/day to 3.0 - 4.0 mm/day depending upon the soil characteristics (infiltration rate), cropping intensity, climate, crop type and salinity management.

Most of the drain spacing equations are developed to meet specific characteristics of a particular area. Some equations assume steady that flow conditions which is applied in areas where longlasting rainfall of more or less uniform intensity prevails. The steady state condition is also exist when the recharge intensity equal to the drainage discharge over the drained area and consequance the water table remains in position. The steady state condition have been presented by several formula, i.e., Hooghoudt, Kirkham, Dagan, and Ernst; which will be presented in this study.

The other type of drainage equations is the non-steady state equations. In this concept, the water table fluctuates with time due to non-steady state recharge or irrigation. This type of equations is the most suitable to calculate the drain spacing in irrigated areas for the following reasons:

- it describe the water table behaviour that conferms to the situation in the irrigated fields.
- it describe the water movement through the soil and also describe the hydraulic head which is not constant and varies with time.
- it considers the soil physical properties which may affect the drainage conditions.

CONCEPT OF CALCULATING DRAIN SPACING USING SPREADSHEET

To facilitate the designers of the subsurface drainage system with a simple tools to calculate the drain spacing; the nomographs and graphical solutions were introduced by number of authors. Due to the introduction of computer aid design in drainage systems, it becomes more important to calculate the drain spacing using simpler technique which allow the users to test and analysis the input parameters and the results interactivily.

The presented spreadsheet package will allow these facilities in different design approaches as follows:

Steady State Options

The selected drain spacing equation in steady state appraoch are: Hooghoudt, Kirkham, Dagan and Ernst equation. This equation could be written as:

$$\frac{4KH}{q}(2d+H) - L^2 = 0 \qquad (3)$$

$$\frac{ql}{K} \cdot \frac{1}{1-(q/k)} \cdot F_k - H = 0 \tag{4}$$

$$L^2 - 8\,D\beta \,.\, L - \frac{8KD}{q} h = 0 \tag{5}$$

$$L^2 + \frac{8D}{\pi} Ln \frac{D}{u} .L - \frac{8KD}{q} h = 0 \tag{6}$$

where,

H = total hydraulic head or water table height above drain level at midpoint (m)

q = drain discharge rate per unit surface areas (m/day)

L = drain spacing (m)

k = hydraulic conductivity of the soil below the drain level (m/day)

Dt = thickness of the aquifer below drain level (m)

u = wet perimeter of the drain (m)

d = equivalent depth of flow to correct for convergence of flow around the drain. It can be calculated according to the formulas developed by Bureau of Reclamation as follow:

when, $D/L <= 0.31$

$$d = \frac{D}{1+\frac{D}{L}(2.55 \ln \frac{D}{r_q} - C)} \tag{7}$$

and when $D/L > 0.31$

$$d = \frac{L}{2.55(\ln \frac{L}{r} - 1.15)} \tag{7b}$$

where, r is the outside diameter of drain pipe, and
$C = 3.55 - 1.6\, D/L + 2\, (D/L)^2$

F_k = Kirkham convergence coefficient which can be calculated according to Tokoz and Kirkham (1961) graphically or from the following approximation

$$Fk = \frac{1}{\pi}(Ln \frac{L}{\pi} r + \sum^{n=\infty} \mathrm{1OVERn}(\cos(\mathrm{2nSMALLPRODrOVERl}) - \cos n\pi).\coth(2n\pi)) \tag{8}$$

β = Dagan function which can be calculated as:

$$\beta = \frac{2}{\pi} \ln \left(2\cosh \frac{\pi r}{D} - 2\right) \tag{9}$$

For the design of parallel subsurface drainage systems, the computation of drain spacing using one of the above equations is required. The most common input required for any of these equations are: q, r, K, H, and D. Since the drain spacing L depends on the equivalent depth d, which in turn is a function of L in both equations (3) and (4); non of these equations can give the computed L explicitly. The presented study, the trail and error procedure based on the Newton-Raphson techniques have been used. The general form of the Newton method is as follow:

$$L = x_n - f(x_n) \cdot \frac{x_n - x_{n-1}}{f(x_n) - f(x_{n-1})} \tag{10}$$

in which x_n first guessed value of L which may be considered as 100x4KH

x_{n-1} the second guessed value of L which may be considered as 1.5 of the first guessed value

$f(x_n)$ value of equation (3) or (4) evaluated at x_n

$f(x_{n-1})$ value of equation (3) or (4) evaluated at x_{n-1}

The resultant value of L is compared with the lost guessed value and it replace it. By this means, the irrational roots can be determined to any desired accuracy.

Calculating the drain spacing using Equ. (5) or Equ. (6) follows another procedure in which the roots of second order equation are evaluated. The general form of the calculated L is written as:

$$L = \frac{-B + -\sqrt{(B^2 - 4C)}}{2} \tag{11}$$

in which, B and C values are parameters calculated according to the formula used.

Non-steady State Option

The Glover-Dumm and Amer-Luthin equations are the nonsteady state equations that have been used in this study. Both equations are particularly used to calculate the drain spacing in irrigated areas, or to calculate the groundwater correspondence to the irrigation and drainage conditions. Each equation require the determination of the soil properties K, D and μ, the geometry of the drains and a drainage criterion. This type of condition requires also the water table drawdown criterion in a certain time. These equation can be written as:

Glover-Dumm:

$$\pi \cdot \frac{\frac{kdt}{\mu}}{(\mathrm{Ln}1.16\frac{h_o}{h_t})} - L^2 = 0 \qquad (12)$$

Amer-Luthin:

$$\frac{K_t/\mu}{F(L/2).\mathrm{Ln}\frac{h_o}{h_t}} - L = 0$$

where:

μ = drainable pore space of the soil (%)
h_o = initial water table height midway between drains (m)
h_t = water table height midway drains after a certain time (t)

Both equations have been solved for drain spacing using the same approach explained above.

PROGRAM APPLICATION

The spreadsheet program provide drainage designers by different options of drainage design concepts through the usage of menu bars and pulldown menus. It has the facilities to interact directly to input/output data using dialog boxes, warning message from the system to user for magnitude value of each parameter used. The advantage of such program that it can be used in sensitivity analysis of any parameter and to study how it can affect the drainage system design. Moreover the graphical presentation provided by the program could help to understand some facts in drainage system. The following application can provided:

Computation of drain spacing

Given the hydrological input data as follow :

- average water table height above the drain level = 0.6 m
- average hydraulic conductivity = 0.8 m/day
- depth of drain barrier below drain = 5 m
- radius of drain pipe = 0.1 m

The calculated drain spacing using steady state option gives 87, 82, 117 and 87 m. ,when Hooghoudt, Kirkham, Dagan and Ernst equation have selected respectively. Using the same input data and applied to sets of nomographs of the same equation the results of drain spacing found 84, 85, 88 and 87 m respectively. The difference between the drain spacing calculated from each equation may be due to the approach used to describe the equivalent drain depth.

Sensitivity analysis of the drainage equation

Table 1 shows the result of calculating the drain spacing using different steady state equation. The hydraulic conductivity used were vary from 0.5 m/day to 5.0 m/day to represent wide range of soil types. The designed drainage rate were varied from 1 mm/day to 3 mm/day to consider the crop type and crop intensity users can extract several facts from such analysis where wider drain spacing will be required in light soils. Narrow drain spacing are recommended in case of lightly crop intensity due to the high drainage discharges. Using the spreadsheet different result can be obtained due to the change of drain radius, depth of drain barrier and the height of the water table above drain level.

K (mm/day)	Hooghoudt			Kirkham			Dagan			Ernst		
	q (m/day)			q (m/day)			q (m/day)			q (m/day)		
	0.001	0.002	0.003	0.001	0.002	0.003	0.001	0.002	0.003	0.001	0.002	0.003
0.5	105	70	54	99	65	50	145	110	95	105	71	56
1.0	155	105	83	149	99	78	194	145	123	154	105	84
1.5	194	132	105	186	126	99	232	171	145	192	132	105
2.0	227	155	124	218	149	118	264	194	163	224	154	124
2.5	256	176	140	247	168	134	292	214	179	252	174	140
3.0	282	194	155	272	186	149	317	232	194	278	192	154
3.5	306	211	169	296	203	162	341	248	207	301	209	168
4.0	329	227	182	318	218	175	363	264	220	323	224	180
4.5	350	242	194	338	233	186	383	278	232	344	239	192
5.0	370	256	206	358	247	198	403	292	243	363	252	203

Table 1. Sensitivity analysis for unsteady state drainage spacing equations by varying the hydraulic conductivity (K) and drainage rate (q)

Effect of drain barrier

The expression introduced by Bureau of Land Reclamation (Eq. 7) to account for the extra resistance caused by the radial flow can be analyzed using the spreadsheet program. It was concluded that the equivalent depth is a function of L,D and radius of the drain. Considering the radius of the drain is constant and equal to 0.1 m. Figure 1 shows how the equivalent depth affect on the calculation of drain spacing. Therefore a field investigation of drainage parameters are highly recommended . Also it can explain the fact that in wider drains spacing the flow pattern toward the drain is different that the one in areas with closely drain spacing. So the result of monitoring the drainage performance could be explained and evaluated.

Water table response to drainage conditions

Using the nonsteady state option,the response of water table between drains due to irrigation can be studied. The effect of the existing drainage condition (drain spacing, depth of barrier, hydraulic conductivity,...etc) could be consider in analyzing this phenomena. Figure 2 shows the water table height above the drain level after irrigation and between irrigation interval for different type of soil which may varied in hydraulic conductivity. The drains was spaced on 30 m. Such graphs could be obtained when the depth of drain barrier changed and also the drain spacing. Such result will be very helpful in water management planning.

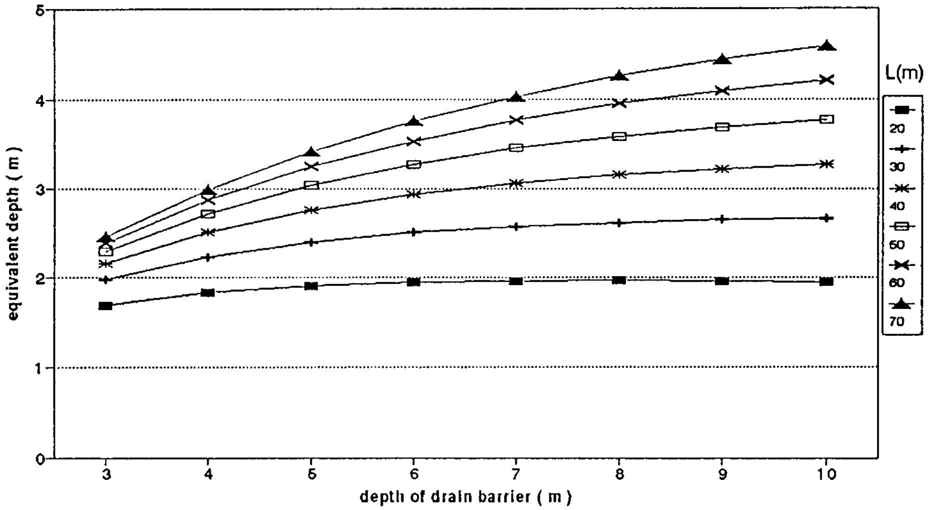

Figure 1. The effect of the equivalent depth on drain spacing

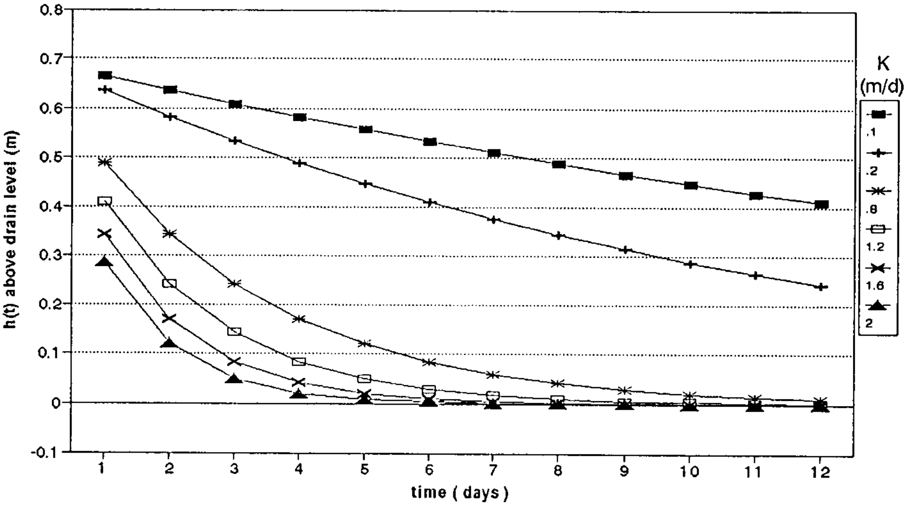

Figure 2. Groundwater height above drain level as affected by soil hydraulic conductivity

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Session 2 - *2^e session*

Quality of Drainage Water and Environment Concerns

Environnement et qualité des eaux de drainage

NUMERICAL SIMULATION OF SOLUTE TRANSPORT IN A TILE- DRAINED SOIL- AQUIFER SYSTEM

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ABSTRACT. A two-dimensional finite element model of solute transport in a tile-drained soil-aquifer system has been applied to study the effects of the depth of impervious layer and quality of irrigation water on salt distribution during drainage of an initially highly saline soil. The model assumes steady state water movement through partially saturated soil and to drains in the saturated zone. The exact in time numerical solution yields explicit expressions for concentration field at any future time without having to compute concentrations at intermediate times. The model facilitates predictions of long-term effects of different irrigation and drainage practices on concentration of drainage effluent and salt distribution in the soil and groundwater. The model results indicated that the depth of impervious layer from drain level, D, does not significantly influence the salt distribution in the surface 1 m root zone of different drain spacings (drain spacing (2S)= 25, 50, 75 m; drain depth (d)= 1.8m); its effect in the aquifer becomes dominant as drain spacing increases. It was also observed that D significantly governs the quality of drainage effluent. The salinity of drainage water increases with increasing D in all drain spacings and this effect magnifies with time. The model was also applied to study the effects of salinity of irrigation water in four drain spacing-drain depth combinations: (2S= 48m, d=1.0m; 2S= 67m, d= 1.5m; 2S= 77m, d= 2.0m; 2S= 85m, d = 2.5m). The results indicated that a favorable salt balance can be maintained in the root zone even while irrigating with water upto 5 dS/m salinity in drains installed at 48 to 67 m spacing and 1.0 to 1.5 m depth. Further, irrespective of the quality of irrigation water, the deep, widely spaced drains (d= 2.5m, 2S= 85m) produced much saline drainage effluent during the initial few years of operation of the drainage system than the more shallow, closely spaced drains, thus posing a more serious effluent disposal problem.

RESUME. *Considérant les conséquences potentiellement sérieuses de la pollution du sol et de l'eau souterraine dans l'agriculture irriguée, il est devenu absolument nécessaire de développer des modèles de simulation en vue d'évaluer les effets à long terme des méthodes agricoles modernes. Un modèle d'éléments finis à deux dimensions du transport en solution dans un système de sol aquifère drainé au moyen de tuyaux a été développé et validé sur le terrain (Kamra et al., 1991 a,b). Le modèle assume le mouvement de l'eau à régime constant à travers un sol partiellement saturé et jusqu'aux drains dans la zone saturée. La solution numérique exacte dans le temps produit des expressions explicites pour le champ de concentration à un temps futur quelconque sans avoir à calculer les concentrations aux temps intermédiares. Le modèle facilite les prédictions des effets à long terme des diverses méthodes d'irrigation et de drainage sur la concentration des effluents de drainage et sur la distribution de la salinité dans le sol et dans l'eau souterraine. Les résultats du modèle relatifs aux effets de la profondeur de la couche imperméable et de la qualité de l'eau d'irrigation sur la distribution de la salinité lors du drainage d'un sol fortement salé à l'origine sont mentionnés dans la présente communication.*

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Les résultats du modèle ont indiqué que la profondeur de la couche imperméable depuis le niveau du drain, D, n'influence pas d'une façon significative la distribution de la salinité dans la zone superficielle radiculaire de 1 m des divers écartements de drains (écartement de drains, 2S= 25, 50, 75 m; profondeur des drains, d= 1,8 m); son effet dans l'aquifère devient dominant à mesure que l'écartement des drains augmente. On a aussi constaté que le niveau du drain D influence d'une manière significative les effluents du drainage. La salinité de l'eau de drainage augmente à mesure que D augmente pour tous les écartements de drains et cet effet s'amplifie avec le temps. Le modèle a aussi été appliqué pour étudier les effets de la salinité de l'eau d'irrigation dans le cas de quatre combinaisons d'écartement de drain et de profondeur de drain: (2S= 48m, d= 1,0m; 2S= 67m, d= 1,5m; 2S= 77m, d= 2,0m; 2S= 85m, d= 2,5m). Les résultats ont indiqué qu'un bilan de salinité favorable peut être maintenu dans la zone radiculaire même en irrigant avec de l'eau d'une salinité de 5 dS/m dans des drains installés à un écartement de 48 à 67m et une profondeur de 1,0 à 1,5 m. De plus, indépendamment de la qualité de l'eau d'irrigation, les drains profonds à grand écartement (D= 2,5m, 2S= 85m) produisent une grande quantité d'effluents salés de drainage durant les quelques premières années de l'exploitation du système de drainage par rapport aux drains peu profonds à écartement faible, posant ainsi un problème plus sérieux d'évacuation des effluents.

Les résultats du développement et de l'évaluation du modèle ont montré qu'il peut être utilement employé en vue d'une évaluation judicieuse de la variation de temps escomptée dans la salinité des effluents de drainage lors de la mise en valeur des sols salins et peut ainsi aider à formuler son règlement plus sûr du point de vue environnement et des projets d'évacuation.

INTRODUCTION

Drainage is generally required to combat the twin problems of waterlogging and soil salinity and to ensure sustained irrigated agriculture in the arid and semi- arid regions. While the benefits of drainage can be counted in terms of improved crop yields and increased economic gains, environmental considerations related with the disposal of saline drainage effluents, sometimes also containing high concentrations of plant nutrients, trace elements and pesticides, impose severe constraints on the design and operation of drainage and related water management projects (Tanji, 1990). Reliable long-term estimates of the volume and composition of draiange effluent in time are required to plan sustainable strategies for its disposal or treatment. Simulation models are generally required to predict the long-term consequences of the management decisions on the performance of drainage systems and evolving a working balance between the maintenance of agricultural productivity and protection of natural resources.

Several simulation models of saturated-unsaturated water flow have been developed to relate drainage system design to soil properties and climatic conditions (Skaggs, 1978; Feddes et al., 1978; Belman et al., 1983; Lesaffre and Zimmer, 1988). The scope of these models has now been extended for arid and semi-arid regions to study the effect of a given design on the salt distribution in the soil profile and or quality of drainage water (Pickens et al., 1979; Nour el-Din et al., 1987 a,b; Tracy and Marino, 1989; Evans et al., 1989; Kamra et al., 1991 a,b). Numerical models, based on standard finite difference or finite element techniques, transform the space derivatives of the governing partial differential equations of water and or solute transport into a finite set of approximate algebraic equations. The time derivative is mostly discretized by iterative finite differences which involve marching through the intermediate time steps to develop solution at the desired time. Kamra et al. (1991a, b) used a semi-discrete approach in which only space was discretized and an exact in-time analytical solution of the system of ordinary differential equations yielded explicit expressions for the concentration field at any future time without needing to compute it at the intermediate times. The two dimensional finite element model of Kamra et al. (1991 a,b) simulates solute transport in tile-drained lands under assumptions of steady state water flow in the unsaturated and saturated zones, and includes the effect of convective transport, dispersion and linear adsorption. The model provides long-term predictions of the desalinization of a tile-drained soil, and of the associated changes in the quality of the groundwater and the drain effluent.

The basic features of the model, and its calibration and field validation are briefly discussed and the model applications on the effect of depth of impervious layer and the quality of irrigation water on transient movement and distribution of dissolved chemicals in tile-drained soil-aquifer system are presented in this paper.

MODEL FORMULATION

Fig. 1 schematically shows the movement of water and dissolved solutes to parallel drains in a tile-drained soil-aquifer system. The space co-ordinate X is positive towards right, whereas Y is positive downward. Infiltrating rain and irrigation water is assumed to flow vertically downward through the partially saturated soil before reaching the arch shaped steady state ground watertable, DE. After reaching the water table, water and dissolved salts move two-dimensionally towards the parallel drains.

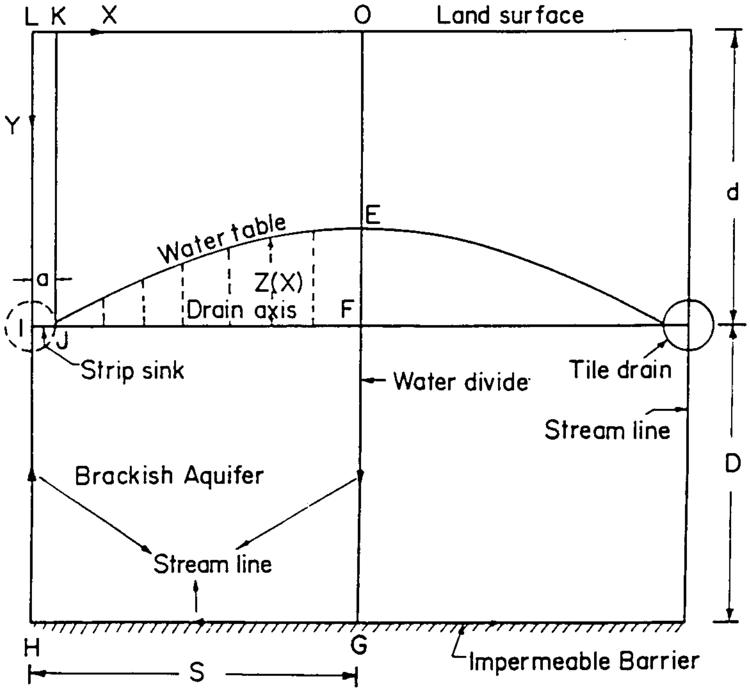


Figure 1. Flow domain for solute transport in a tile-drained soil-aquifer system

Consider the governing equation of two dimensional solute transport in unsaturated-saturated porous media (Kamra et al. 1991 a)

$$\theta R_f \frac{\partial C}{\partial t} = \frac{\partial}{\partial X}(\theta D_{xx} \frac{\partial C}{\partial X} + D_{xy} \frac{\partial C}{\partial Y}) + \frac{\partial}{\partial Y}(\theta D_{yx} \frac{\partial C}{\partial X} + \theta D_{yy} \frac{\partial C}{\partial Y})$$

$$- [\frac{\partial}{\partial X}(q_x C) + \frac{\partial}{\partial Y}(q_y C] + \Phi (X,Y,t) \qquad (15)$$

in which C is the dissolved solute concentration (M/L^3), R_f is the retardation factor, θ is the volumetric water content (equal to porosity in the saturated zone)(L^3/L^3); D_{xx}, D_{xy}, D_{yx}, D_{yy} are the components of dispersion coefficient tensor (L^2/T), q_x and q_y are the Darcian specific discharge components, (L/T), and $\Phi(X,Y,t)$ is a source or sink term, being positive for sources and negative for sinks (M/L^3T), X and Y are space coordinates (L), and t is time (T). The retardation factor R_f in (1) accounts for linear equilibrium interactions between the solute and the porous medium and is given by $R_f = 1 + \varepsilon_3 K_d / \theta$ where ε is the bulk density of porous medium (M/L^3) and K_d is a solute distribution coefficient (L^3/M). The dispersion coefficients for a two-dimensional isotropic porous medium were adopted from Scheidegger (1961) which relate D_{xx}, D_{xy}, D_{yx} and D_{yy} to q_x, q_y, θ, q, α_L and α_T where α_L and α_T are the longitudinal and transverse dispersivities (L), respectively and q is the magnitude of specific discharge vector (L/T).

Steady State Water Movement

Wierenga (1977), Beese and Wierenga (1980) and Destouni (1991) have shown that transport models based on steady state water flow can produce concentration distributions that are comparable to those obtained with transient water flow models, but with considerably less input data requirements than the transient models. The steady state formulations can be particularly useful for making long-term predictions by ignoring the often highly dynamic but short-term oscillations in water content and solute concentration near the soil surface. Accordingly steady state water flow models were used in this study for both the unsaturated and saturated zones.

Unsaturated zone

The velocity field for the unsaturated part of the flow domain was obtained by considering the water flow to be vertical (q_x = zero) and taking q_y equal to the net upward or downward steady state flux. The net water flux during a period was obtained from the water balance of the area and a reliable estimate of the groundwater contribution to evaporation. The Darcy law equation was numerically integrated to compute pressure heads (and consequently moisture contents provided the water retention and hydraulic properties of soil are known) at required heights from water table during steady upward or downward water flow. The functional forms of unsaturated hydraulic properties used in this study were those of Van Genuchten (1978).

Saturated Zone

Kirkham (1958) analytically solved the Laplace equation for the watertable height, Z, above the drain axis, and the hydraulic head distribution in the flow domain ABCDFA below the drain axis (Fig.1) for a homogeneous aquifer. The specific discharge components, q_x and q_y, were computed for the region ($0 \leq X \leq S$, $0 \leq Y \leq D$) with the help of Darcy's law (Kamra, 1989). Solutions are applicable to other half of the domain between the two drains because of symmetry.

Initial Conditions

The measured solute concentration in the flow domain before the beginning of the simulation period is taken as the initial condition:

$$C(X,Y,0) = C_0(X,Y) \text{ at } t = 0$$

Boundary Conditions

The solute flux is prescribed on a Cauchy boundary, the normal gradient of concentration on a Neumann boundary, while concentrations are prescribed on Dirichlet boundary nodes. A Cauchy boundary condition is generally applied to a boundary through which solute enters the region. The Neumann boundary conditions are imposed on flow-through boundaries with outflow from the region, and on impervious boundaries. The land surface KO (Fig.1) acts as a Cauchy boundary during the infiltration phase and the segments HG (bottom basis layer), OG (water divide), and HI and JK (streamlines) are treated as impervious boundaries. The tile surface IJ and land surface KO during evaporation are outflow boundaries. There are no Dirichlet boundaries in the present study.

Finite Element Solution

The Galerkin finite element method was used to simulate solute transport in tile-drained soils. The procedure involves discretization of the flow domain into finite elements and using approximate basis functions to interpolate concentration within each element. Quadrilateral elements and linear basis functions were employed in this model to approximate equation

(1) with a vector-matrix differential equation of the following form :

$$[AM] \{dC/dt\} = [DM] \{C\} + \{F\} \tag{2}$$

where

[AM]	NN x NN symmetric coefficient matrix;
[DM]	NN x NN nonsymmetric matrix accounting for convection, dispersion and outflows boundaries;
{F}	NN x 1 vector representing the sources/sinks, and boundary conditions of the transport equation;
{C}	NN x 1 vector of nodal concentrations;
NN	number of nodes in the discretized domain at which the concentration is unknown.

The typical elements of these matrices, the finite element evaluation of spatial derivatives of equation (1) and the application of initial and boundary conditions has been presented in Kamra et al.(1991a).

Solution of Vector-Matrix Diffential Equation:

Kamra et al. (1991 a) presented the solution of the inhomogeneous matrix-vector equation (2) for time invariant boundary conditions as :

$$\{C\} = e^{[H]t} \{\{C_o\} + [DM]^{-1} \{F\}\} - \{[DM]^{-1} \{F\}\} \qquad (3)$$

where [H] is a NN x NN matrix equal to $[AM]^{-1}$ [DM]. The eigenvalue-eigenvector method of Euler was used to compute the matrix exponential, $e^{[H]t}$, which is a matrix of same dimensions as [H]. The eigensystem may be complex (i.e. it may have imaginary components) due to asymmetry created by the convection term in the governing convection-dispersion equation. The matrix exponential $e^{[H]t}$ was computed from the relationship (Kamra et al., 1991a):

$$e^{[H]t} = [Z]\, e^{[D]t}\, [Z]^{-1} \qquad (4)$$

where [Z] is a NN x NN matrix whose columns are the eigenvectors of [H], and [D] is a NN x NN diagonal matrix whose entries are the eigenvalues of [H]. Once the eigensystem of [H] is obtained, (4) can be used to compute $e^{[H]t}$ which can then be used in (3) to compute C(t), the concentration field at any time in the future.

MODEL CALIBRATION AND FIELD VALIDATION

The model was validated against field results of a sub-surface tile drainage experiment of Central Soil Salinity Research Institute, Karnal (India), conducted on its Saline Soil Research Farm at Sampla (District Rohtak) in the State of Haryana. Sub-surface drainage system, consisting of thrice replicated three drain spacings of 25, 50 and 75m and average drain depth of 1.80 m, was installed at Sampla in the summer of 1984 in a 10 ha saline area. The soil salinity (EC_e, electrical conductivity of the saturation extract) of the surface 15 cm soil in the area ranged from 20 to 100 dS/m. The salinity was about 30 dS/m in the 15-30 cm layer and 20 dS/m below 30 cm. Dissolved salts were mainly calcium, magnesium and sodium chlorides. Before installation of the drains, the watertable in the area typically fluctuated between a depth of 1.5 m (during early summer) and the soil surface (during the rainy season). Salinity of the groundwater near the watertable varied from 10-40 dS/m. The soil in the region is a sandy loam alluvium having hydraulic conductivity of 1.0 m/day upto 1.75m depth, followed by a loamy sand zone of 3 m/day hydraulic conductivity . This porous zone extends to a fine textured layer of low permeability at 3- 4 m which was treated as the impermeable boundary (Rao et al.,1986). The values of selected hydraulic and drainage system parameters, including steady annual water fluxes, are listed in Table 1.

Parameter	Value(s)
Drain Spacing, 2S	25,50,75 m
Drain Depth, d	1.8 m
Depth of impervious layer below drain axis, D	1.2, 2.0, 5.0 m
Saturated hydraulic conductivity of aquifer,K_S	3.0 m/day
Soil water retention parameters	
(van Genuchten, 1978)	
K_S	1.0 m/day
θ_S	0.4486
θ_r	0.1004
α	0.0088 1/cm
n	1.6715
m	0.4017
Soil bulk density, ε	1.5 g/cm^3
Distribution coefficient (cm^3/g)	K_d 0.0
Longitudinal dispersivity, α_L Transverse dispersivity, α_T	0.8 m 0.08 m
Annual steady water flux for 25, 50 and 75m drain spacing	1.0, 0.7, 0.4 mm/day

Table 1. Values of Selected Soil Hydraulic and Drainage System Parameters

The observed seasonal drain discharge rates, after correcting for estimated lateral seepage and upward water fluxes from watertable during summer in individual plots, were combined to compute annual water fluxes which were highly variable for different drain spacing plots. Numerical results corresponding to different values of longitudinal dispersivity, α_L, were used for calibrating the model to observed soil solution and drain effluent concentrations during 1984 and the selected value of α_L was used to validate the model against field observations of 1985. The transverse dispersivity, α_T, was assumed to be always one tenth of α_L. The model was then applied to make 10 year predictions on salt distribution in soil, groundwater and drainage effluent. Further details on the calibration, field validation, long- term predictions and sensitivity analysis of a number of model parameters can be found elsewhere (Kamra et al., 1991 b).

RESULTS AND DISCUSSION

The results related with longterm effects of the depth of impervious layer and salinity of irrigation water on salt distribution in tile-drained lands are discussed below:

Effect of depth of impervious layer

From field observations of hydraulic head and drain discharge, the average depth of the impervious layer, D, at Sampla was estimated at 1.2 m below drain axis (Rao et al., 1986). The model results corresponding to three values of D (=1.2, 2.0 and 5.0 m) on salt distribution in the soil profile and the aquifer at midplane of different drain spacing plots, two and five years after operation of drainage system, are presented in Fig.2. The results for aquifer in all drain spacings were restricted to a depth of 2.7 m from drain level below which salinity at any time did not vary with depth. These observations are similar to water movement results of Childs (1943) which indicated that about 75 % of the total flow to a field drain in a deep homogeneous soil takes place within a depth equal to 1/20 of the drain spacing from the drain axis.

The depth of impervious layer, D, had little influence on the salt distribution in 1.0m effective root zone of all drain spacings (Fig. 2) mainly because the water movement was assumed to be steady and its equation for the unsaturated zone (Kamra et al., 1991 a) did not account for D. The small differences in individual drain spacing plots can be attributed to differences in moisture distributions due to different watertable profiles obtained with different values of D. However, because of increase in saturated flow domain with increasing D, its effect on salt distribution in aquifer increased; the effect becoming more pronounced with increasing drain spacing. The model results for 50 and 75 m drain spacings also indicated the aquifer at 1.2 m from drain level to be relatively more saline when D is equal to 1.2 m than the case when $D \leq 2.0$ m. As discussed by Child (1969), the sections EFG, GH and HI (Fig. 1) of the flow domain constitute a bounding streamline. The refered zone for D = 1.2 m (point G in Fig.1) represents a stagnation point where, due to $\pi/2$ change in direction of streamline, the flow velocity becomes zero resulting in little improvement in the salinity of the region. Similar behaviour was also observed in corresponding areas for cases when D is equal to 2.0 and 5.0 m. Point H (Fig. 1) is another stagnation point which, though not discussed in Fig. 2, showed little improvement in salinity.

Figure 3 presents the effect of D on the time variation in the salinity of drainage effluent, EC_d, in different drain spacings. It is observed that the depth of impervious layer significantly governs the quality of drainage effluent. EC_d in all drain spacings increased with increasing D, apparently due to extension of saline groundwater domain, and the effect magnified with time. In the first two years, the differences in EC_d due to increasing D are seen to be more dominant in the closer drains. This is because during initial stages of reclamation, the salts leached from soil profile contribute more than the salts drained from aquifer towards the salt load of drainage effluent. Since leaching is more efficient (faster) in closer drains, this trend continues for a longer period in widely spaced drains. After initial 2-3 years, the fraction of salts leached from soil profile decreases and the effect of D on EC_d manifests itself more significantly.

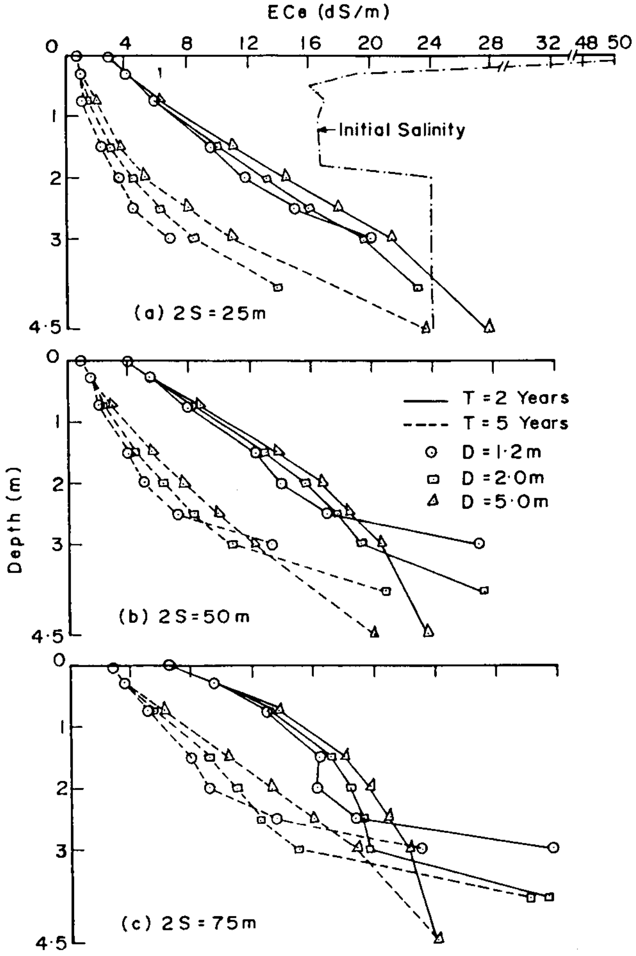


Figure 2. Effect of depth of impervious layer, D, on salt distribution in soil profile and aquifer

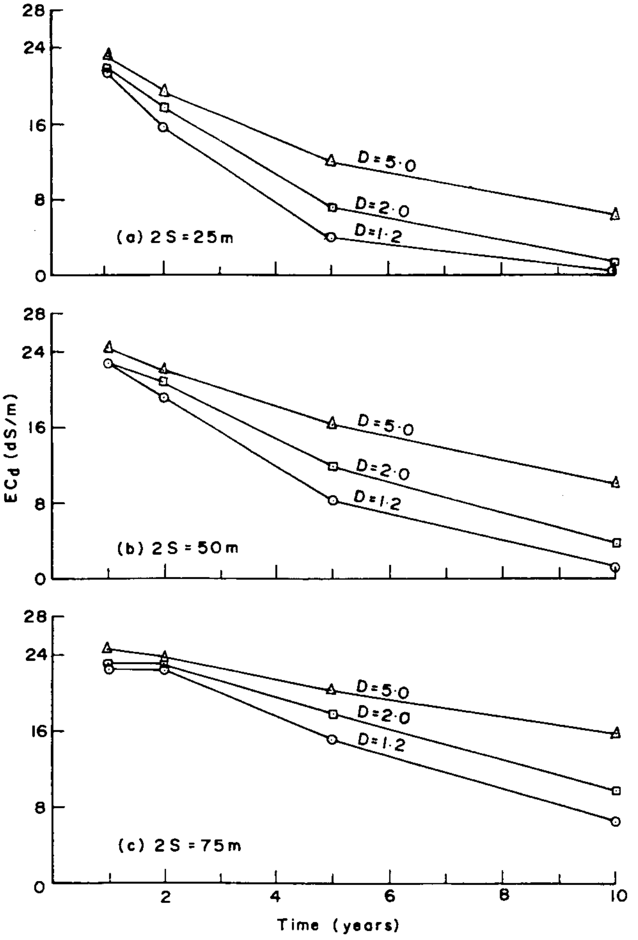


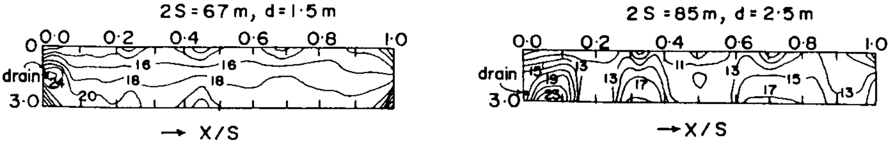
Figure 3. Effect of depth of impervious layer, D, on salinity (EC_d) of drainage effluent.

Effect of quality of irrigation water

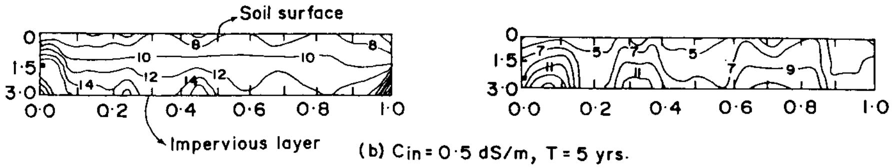
The model was also applied to study the effect of salinity of irrigation water on solute transport under alternate drainage designs. Four drain spacing (2S)- drain depth (d) combinations: 2S = 48m, d = 1.0m; 2S = 67m, d = 1.5m; 2S = 77m, d = 2.0m; 2S = 85m, d = 2.5m, having drain discharge vs. hydraulic head relationships identical to those of the recommended combination of 2S= 75m, d= 1.8m for Sampla, were used in the comparison. The iso-salinity contours within the flow domain, corresponding to two salinities (C_{in} = 0.5 and 5.0 dS/m) of irrigation water, for 2S = 67m, d = 1.5m and 2S = 85m, d = 2.5m are presented in Fig. 4, and the time variation in the salinity of drainage effluent for the four designs are presented in Fig. 5.

The results indicate that irrespective of the salinity of irrigation water upto 5 dS/m, the desalinization of the soil profile is more effective with the deeper drains. However, the shallower drains are also reasonably effective in rapidly reducing the salinity of top 1 m soil profile that is involved with crop production. It is seen from Figs. 4b and 4c that an increase in C_{in} from 0.5 dS/m to 5.0 dS/m in 1.5 m deep drains increases the salinity of effective root zone and of aquifer after five years from 9 to 12 dS/m and 12 to 14 dS/m, respectively. The corresponding increases for root zone and aquifer in 2.5 m deep drains are from 6 to 10 and 10 to 12 dS/m respectively, indicating marginal longterm advantage of deeper drains in using saline irrigation water upto 5 dS/m.

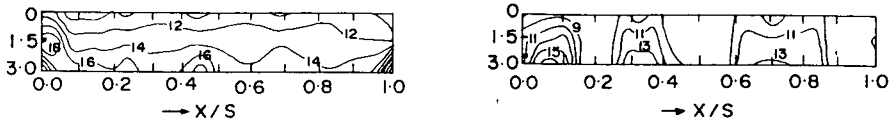
The flow patterns of salt movement in 1.5 and 2.5m deep drains in a 3.0m soil-impervious layer domain (Fig. 4) are quite different. The salinity contours of 1.5m deep drains are almost symmetric around the drain till a lateral distance of 0.05S and uniform (parallel contours) in the remaining area indicating the leaching of salts both from above and below the drain level. In 2.5m deep drains, the convergence (concentration) of salts extends to a lateral distance of 0.15S from the drain, with most of salts from above the drain appearing to be leached through a sink in the bottom impervious layer. The presence of similar sinks farther away from drain are probably due to the appearance of oscillations in numerical results of wider drains with a relatively coarser discretization.



(a) C_{in}=0·5 dS/m, T = 2 yrs.



(b) C_{in}= 0·5 dS/m, T = 5 yrs.



(c) C_{in}= 5 dS/m, T = 5 yrs.

(Length units in m,
—14— in dS/m)

Figure 4. Effect of salinity of irrigation water, C_{in}, on salt distribution in a tile-drained soils for two drain spacing-depth combinations of 2S= 67m, d= 1.5m and 2S= 85m, d= 2.5m.

Figure 5 indicates that, irrespective of the quality of irrigation water, EC_d for the deepest and the most widely spaced drains is higher than for the shallower and closer drains during the first three years, after which it reduces sharply to less than those for the other cases. This is understandable since a much larger soil volume is involved in the leaching process for deeper drains, resulting in an initial much heavier salt load to drains. However, once most of the salts are removed, the soil profile for the deepest drain becomes relatively salt-free and EC_d reduces relatively more rapidly than the shallower drains. Further, it appears that at any time the increase in the salinity of drainage effluent (and also of root zone), corresponding to an increase in C_{in} from 0.5 to 5.0 dS/m, is slightly more in deeper drains (d≥2.0m) than in shallower drains.

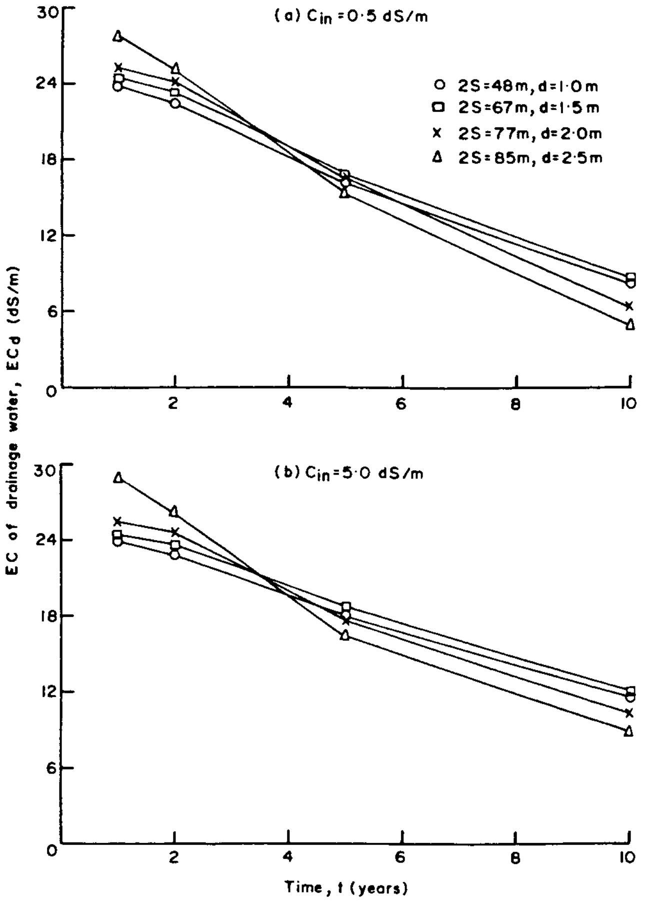


Figure 5. Predicted changes in EC_d in different drainage designs using irrigation water of salinity (C_{in}) (a) 0.5 dS/m and (b) 5 dS/m

SUMMARY AND CONCLUSIONS

A two dimensional finite element model of salt transport in tile drained soil-aquifer system has been presented. The input data requirements of the model include drainage system parameters (such as drain depth, drain spacing, and radius of the drain), aquifer parameters (porosity and hydraulic conductivity of aquifer material, depth to impervious layer, and groundwater salinity), soil parameters (notably the soil water retention and unsaturated hydraulic conductivity functions and initial soil salinity), solute adsorption parameters (the equilibrium distribution coefficients of the saturated and unsaturated zones), and inflow parameters (rainfall, evapotranspiration, quantity and quality of irrigation water).

The model results indicate that though the depth of impervious layer, D, has little effect on root zone salinity; it significantly governs the quality of drainage effluent. The salinity of drainage water increases with increasing D in all drain spacings and this effect magnifies with time. These results emphasize the need of careful and intensive investigations on D in a reclamation project to judiciously assess the expected time variation in the salinity of drainage effluent under alternative drainage designs. This can help to plan and execute environmentally safer disposal and utilizational schemes of the saline drainage water. The model results also indicate that for inland saline sandy loam soils of Haryana, India, favorable salt balance can be maintained in the root zone even while irrigating with 5 dS/m saline water and using sub-surface drains of 48 to 67m spacing and 1.0 - 1.5m depth. The quality of effluent of drains wider and deeper than these limits, especially if installed at depths ≥ 2.5m, is more saline than that of shallower drains during the initial years which may pose a relatively more difficult surface disposal problem.

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DESIGN OF HYDROLOGICAL BUFFER ZONES BETWEEN DRAINED AND NATURAL AREAS

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ABSTRACT. The protection of natural areas by transition or buffer zones involves several scientific issues since biological, ecological, chemical or hydrological aspects may be relevant. Protected wet biotopes are often surrounded by drained agricultural land. In these cases the effect of drainage on the moisture regime of the protected area becomes a very important aspect when designing buffer zones. In practice, evaluating of the required width of such hydrological buffer zones is controversial mainly because of the lack of physically based design methods.

This paper presents the developement of a practical tool to evaluate the required width of a hydrological buffer zone between drained and natural areas. A simple mathematical formulation was used to describe the lateral drawdown extent L of a drained water table in unsteady flow conditions.

Continuous simulation with daily rainfall data is used to generate L(t) series. The evaluation of a single significant L_C value involves the concepts of protection level and threshold of tolerance.

Sensitivity analysis indicates that for any rainfall condition and protection criteria the variations of L_C can be satisfactorily represented by a polynomial approximation. Thus a simplified method in which rainfall no longer appears explicitely has been developed and implemented on the spreadsheet program EXCEL.

An application of this method to the protection of a peat bog system in the Swiss Jura region is presented.

RESUME. Dimensionnement de zones tampon hydrologiques entre terrains drainés et milieux naturels. *La protection de biotopes humides, souvent situés à proximité de zones drainées, peut être recherchée par la création de zones de transition destinées à limiter les effets perturbants que peuvent avoir les activités agricoles sur ces milieux. Pour être efficaces, ces zones tampon doivent avoir une dimension suffisante du point de vue trophique (migration de fertilisants), biologique (compétition entre espèces), hydrologique (stabilité du régime hydrique) et écologique (fonctions, intégration à un réseau). Simultanément, leur dimension ne doit pas être excessive pour ne pas nuire au bon fonctionnement des exploitations agricoles, voire dans certains cas menacer leur existence.*

Dans la pratique courante, la largeur des zones tampon est généralement déterminée, au terme d'âpres discussions, par une moyenne pseudo-arithmétique entre les chiffres avancés respectivement les milieux de protection de la nature et par les milieux agricoles. Dans ce

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contexte, la question des effets du drainage sur les nappes phréatiques environnantes donne lieu à de nombreuses controverses.

Cet article décrit la démarche effectuée pour mettre à disposition des praticiens un instrument aisément utilisable permettant d'évaluer la largeur requise par une zone de protection hydrologique destinée à maintenir les effets du drainage sur les milieux voisins dans des limites acceptables.

Cette démarche repose sur une formulation physico-mathématique simple décrivant l'extension latérale du rabattement L de la nappe par un drain en régime variable en fonction des caractéristiques hydrodynamiques du sol (conductivité hydraulique K et porosité de drainage μ) et des caractéristiques morphologiques du système drainant (profondeur des drains P et profondeur de l'horizon imperméable D).

Les séquences L(t) décrivant l'évolution de la distance de L sous l'effet d'une pluviométrie décrite par des données journalières sur plusieurs années sont obtenues par simulation. Le problème de la réduction de ces résultats à une seule valeur représentative L_C conduit à définir les notions de "seuil de tolérance" ou de "degré de protection".

Dans l'optique d'une application pratique, cette méthode présente toutefois l'inconvénient majeur de recourir à des séries pluviométriques longues, d'accès et de manipulation pas toujours aisés, et avec pour corollaire des temps de calculs importants (en particulier pour les analyses de sensibilité qui constituent un aspect essentiel des résultats recherchés). Une méthode approchée, dans laquelle la variable pluviométrique n'apparaît plus de façon explicite, a de ce fait été développée.

Par échantillonnage systématique, des ensembles de valeurs discrètes de fonctions $L_C(K, \mu, P, D)$ correspondant à diverses stations pluviométriques et à divers "seuils de tolérance" ont été ainsi constitués. Ces fonctions présentent toutes une forme régulière similaire, si bien qu'il s'est avéré possible de reconstituer chacune d'entre elle avec une bonne précision par approximation polynomiale de second ordre, à partir d'un ensemble restreint de 270 valeurs représentatives.

Des ensembles de valeurs représentatives ont été constitués pour 4 stations pluviométriques caractéristiques des principales régions drainées de Suisse et pour divers types de "seuils de tolérance". Ces ensembles, de même que les procédures d'approximation polynomiale et d'interpolation ont été intégrés à une application informatique simple, développée sur micro-ordinateur (Macintosh ou PC) à l'aide du logiciel EXCEL. Ce programme permet ainsi non seulement de déterminer rapidement la dimension requise par une zone tampon hydrologique en fonction des paramètres caractéristiques du système, mais également d'effectuer simultanément une analyse de sensibilité dont les résultats se présentent sous forme de graphes.

Une application de cette méthode dans le cadre de la protection d'un système de tourbières du Jura Suisse est présentée.

PROTECTION OF NATURAL WETLANDS

Most natural wetlands show waterlogged soils with a high agricultural potential. Lowering the ground water table by means of subsurface drainage allowed to exploit gradually these areas for agricultural purposes. This resulted in a sharp decrease of the overall wetland areas. Most of the remaining natural wetlands have to be preserved according to protection laws since they shelter numerous endangered plant species and assume vital functions for animal wild life.

As in most western european countries, reclamation of natural wetlands is no longer possible in Switzerland. However, protection of wet natural biotopes is an acute problem when surrounding old and dysfunctionning drainage systems have to be upgraded.

Protection means creating or preserving adequate biochemical and physical conditions (water regime, plant nutriments, biological equilibrium) as well as ensuring an adequate integration in the overall ecological network (functions, access, etc.). Therefore design of a transition stripe or buffer zone surrounding a protected area implies therefore biological, ecological, trophic and hydrological considerations.
In practice, the width of a buffer zone is considered to be equal to the average of those proposed respectively by farmers and ecologists after grim discussion. The effect of subsurface drainage on the water regime of the surrounding areas causes much controversy. This paper describes the research made by the authors to provide a practical tool to evaluate of the extent of the lateral drawdown induced by a drain. The developed method applies only from a hydrological point of view. Users should bear in mind that other considerations are also important.

Since the objective of this research was to develop an easy applicable practical tool, the mathematical description of the process had to remain simple. Data requirements should be minimized. Moreover the method should be implemented on conventional hardware equipment to allow its application with usual calculation means and easily accessible data. Besides, due to the assumptions on which the mathematical model is based and to the uncertainty when measuring physical parameters (mainly hydraulic conductivity) it was felt that sensitivity analysis should also be considered in order to provide confidence intervals rather than a single value.

The very few papers dealing with hydrological buffer zones provide either empirical formulae (Eggelsmann 1977) or specific widths for a given region (Kuntze & Eggelsmann 1981). A formula derived from a more rigorous and analytical approach can also be found (Van der Molen 1981). However the latter only holds for drains lying on an impervious layer and under the assumption of a 6 months' drought period. In Switzerland, existing methods to design buffer zones are mostly concerned with contamination by fertilizers and do not take drainage into account (see for example Krüsi 1986).

MATHEMATICAL FORMULATION

Figure 1 shows a schematic representation of the water table drawdown generated by a drain. Length L [m] is the lateral extent of the drawdown zone, P [m] is the drain depth, D [m] is the depth of the impervious layer below the drains and i [m/s] is the groundwater recharge intensity. Soil is assumed horizontal, homogenous, isotropic and incompressible, with a hydraulic conductivity K and an effective porosity μ.

On the basis of classical Dupuits-Forschheimer assumptions (applicability of Darcy's law and horizontal flow) it can be shown that with a uniform recharge distribution and neglecting lateral inflows, the water table shape is elliptical. Moreover, in the regions where the water table reaches ground surface, any excess precipitation is considered as runoff over saturated soil.

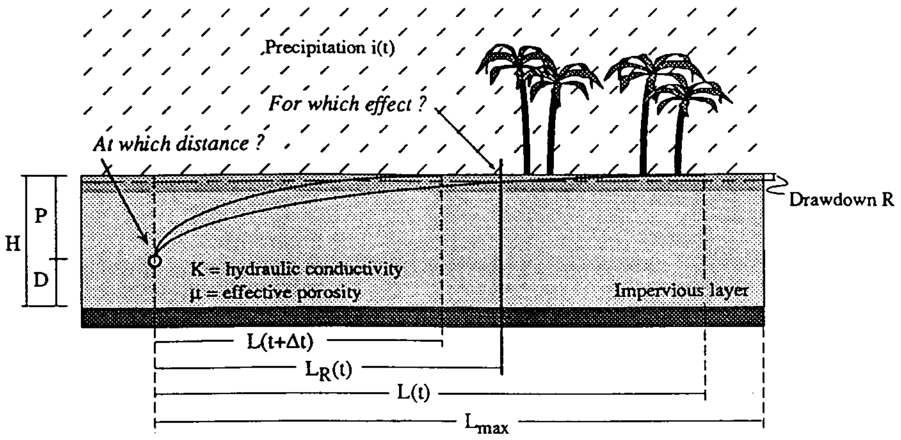


Figure 1. Drainage effect on the surrounding natural areas

According to these assumptions, mass conservation in non steady flow conditions can be written as follows (Perrochet & Musy 1992):

$$Q(t) = i(t) \,.\, L(t) - \frac{\partial V(t)}{\partial t} \tag{1}$$

where $Q(t)$ [m^3/s] is the linear flow at the drain and $V(t)$ [m^3] is the stored free water volume. The latter can be written as follows:

$$V(t) = \mu \,(\frac{\pi}{4} PL(t) + P(L_{max} - L(t) + DL_{max}) \tag{2}$$

Differentiation of equation (2) with respect to time yields:

$$\frac{\partial V(t)}{\partial t} = \mu \,(\frac{\pi}{4} - 1)\, P \frac{\partial L(t)}{\partial t} \tag{3}$$

According to Hooghoudt, the flow at the drain may be written as:

$$Q(t) = \frac{KP^2}{L(t)} + \frac{2KP\, d(t)}{L(t)} \tag{4}$$

where the equivalent depth d is (Wesseling 1983):

$$d = \frac{L}{4\left[\frac{(2L - D\sqrt{2})^2}{16\,DL} + \frac{1}{\pi}\ln\frac{2D}{\Phi\sqrt{2}}\right]} \text{, with } d = 0 \text{ when } D = 0 \qquad (5)$$

where ϕ is the drain diameter. Substitution of equation (3) and (4) in equation (1) yields:

$$\mu = (1 - \frac{\pi}{4})\,PL(t)\frac{\partial L(t)}{\partial t} + i(t)\,L^2(t) = KP^2 + 2KP\,d(t) \qquad (6)$$

Assuming a constant recharge intensity i and a constant equivalent depth d over a time step t [s], integration of equation (6) yields:

$$Lt = \sqrt{(L_0^2 - \frac{KP(2d+P)}{i}\,e^{\frac{8i}{\mu(\pi-4)P}t} + \frac{KP(2d+P)}{i}} \qquad (7)$$

where L_0 and L_t are the drawdown extents at the beginning and at the end of the time step. An equivalent expression for i=0 results from the application of the rule of l'Hôpital to equation (7) (Perrochet & Musy 1992):

$$Lt = \sqrt{L_0^2 + \frac{8K(2d+P)}{\mu(4-\pi)}\,.\,t} \qquad (8)$$

By increasing depth D, the watertable changes gradually from an elliptical to a sinusoidal shape. Consequently for high D values (i.e. P/D ’ 0), the p/4 coefficient in equation (6) should be replaced by 2/p. As long as the water table shape can be considered elliptical, the distance L_R related to a given drawdown R can be written as follows:

$$L_R = L\,.\left(1 - \sqrt{1 - \frac{(P-R)^2}{P^2}}\right) \qquad (9)$$

PROTECTION LEVEL

Equations (7), (8) and (5) are solved iteratively procedure. Daily rainfall data allows to generate L(t) sequences. As shown in figure 2, the choice of an initial L_0 value is no longer significant after a relatively short period.

Reducing the L(t) sequences to a single significant value L_C for design purposes brings up the question of protection goals. For instance, the latter may be given in terms of a drawdown level R that can be exceeded either X times a year or during Y consecutive days every T years without any harmful effects on the vegetation of the protected area. Both kinds of conditions expressed by sets (X, R) or (Y, T, R) define a threshold of tolerance or protection level.

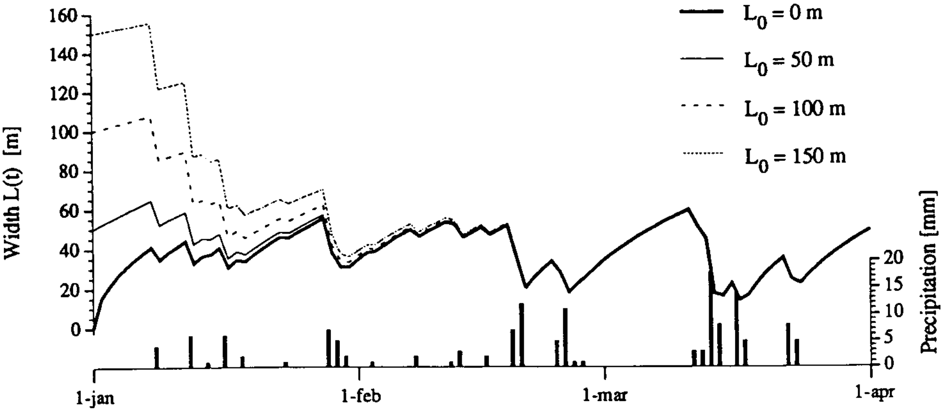


Figure 2. Effect of the initial L_0 condition on a L(t) serie

If the protection level is expressed by the set (X, R), critical values of L_c are derived from L(t) sequences by means of cumulative frequency curves and applying equation (9). For (Y, T, R) sets, frequency analysis of annual maximal values averaged over Y days is used in conjunction with equation (9) are applied.

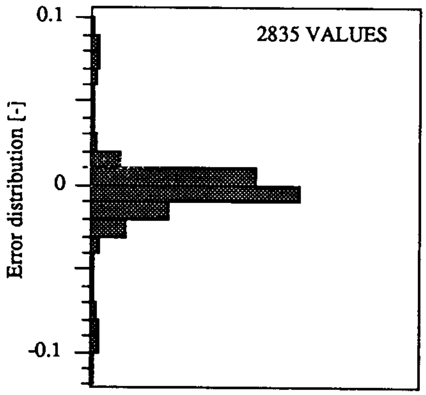
Since water table fluctuation may only affect vegetation during the growing season, only parts of the L(t) sequences ranging from April 1 st to October 31 th have to be considered.

APPROXIMATED METHOD

The above described method requires long daily rainfall data series. Moreover the iterative nature of equations (5) and (7) or (8) leads to long turn around times. This is a major drawback of the method specially when it is reminded that sensitivity analysis is required and that the proposed methodology should be fully operational. It was then decided to develop a simplified method in which rainfall no longer appears explicitly.
Daily rainfall data over 16 years were used to simulate various L(t) sequences using several combinations of parameters (K, μ, P, D) that were systematically varied within reasonable ranges. Applying various (X, R) or (Y, T, R) conditions to the obtained L(t) sequences leads in each case to a set of L_C figures, which are discrete values of a specific L_C(K, μ, P, D) function.

Since the shape of the various L_C functions are similar and show a regular pattern they can be accurately approximated by second order polynomial functions. In the case of K values ranging from 10^{-7} m/s to 10^{-3} m/s, μ values from 0.05 to 0.25, P values from 0.8 to 2.0 m and D values from 0 to 20 m, this approximation requires a set of only 270 representative values.

Figure 3 shows the error distribution occurring when such polynomial functions are used to re-establish the initial 2835 discrete values of an L_C(K, μ, P, D) function. The maximal error is of the order of ± 10 %, while 80 % of the error remains smaller than ± 2 %.

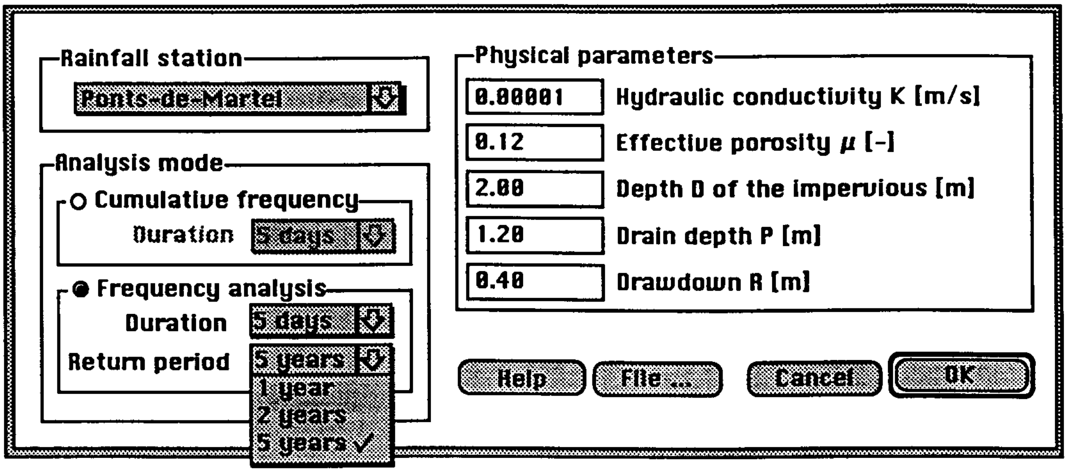


Nb. of values		2835
Average		0.001
Standard deviation		0.03
Maximum	100.0 %	0.10
	99.5 %	0.10
	97.5 %	0.08
	90.0 %	0.02
Quartile	75.0 %	0.01
Median	50.0 %	0.00
Quartile	25.0 %	-0.01
	10.0 %	-0.02
	2.5 %	-0.09
	0.5 %	-0.10
Minimum	0.0 %	-0.12

Figure 3. Error distribution of the approximated L_C values

Sets of representative values were thus determined for four rainfall stations in various regions of Switzerland and several protection levels. For instance X values of 5, 10, 20, 30, 50, 100, 150 and 200 days, Y values of 1, 3, 5, 10 and 20 days, and T values of 1, 2 and 5 years were chosen, the admissible drawdown R ranging between 0 and drain depth P.

These sets of values, as well as the approximation method, were integrated in the spreadsheet program EXCEL, running either on Macintosh or PC compatible computers. This allows a fast and easy evaluation of the critical L_C value for any set of (K, μ, P, D) parameters and (X, R) or (Y, T, R) conditions selected by the user (figure 4). The program also performs a sensitivity analysis resulting in $L_C(K)$, $L_C(\mu)$, $L_C(P)$, $L_C(D)$ and $L_C(R)$ graphics (figure 5).



Rainfall station
Ponts-de-Martel

Analysis mode
○ Cumulative frequency
Duration 5 days
● Frequency analysis
Duration 5 days
Return period 5 years

Physical parameters
0.00001 Hydraulic conductivity K [m/s]
0.12 Effective porosity μ [-]
2.00 Depth D of the impervious [m]
1.20 Drain depth P [m]
0.40 Drawdown R [m]

Figure 4. Selection of parameters and conditions as displayed on the screen

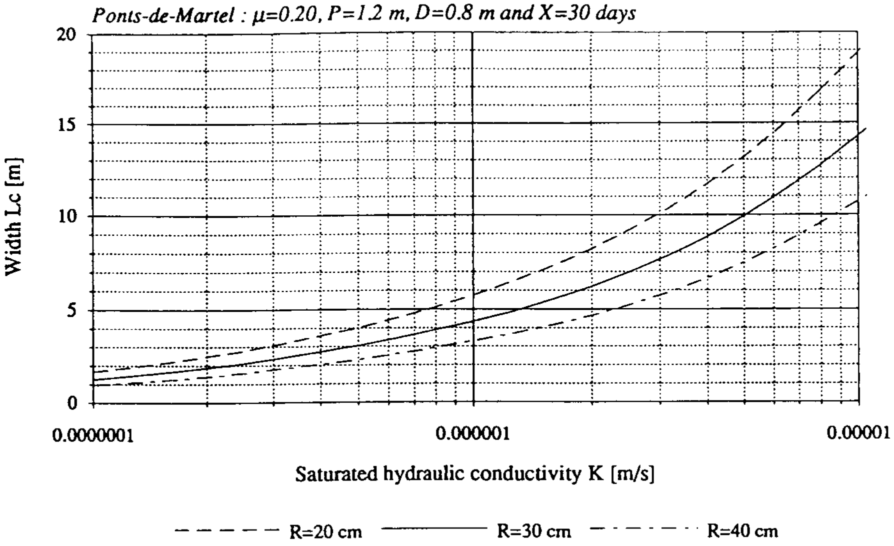


Figure 5. Example of graphical output: width L versus hydraulic conductivity K for several admissible drawdowns R

APPLICATION

The method described in this paper was applied within the frame of a peat bog protection study including the evaluation of the width of hydrological buffer zones. Ponts-de-Martel valley, located 1000 m above sea level in the Jura mountains in western Switzerland, is made of a very weak permeable glacial marl on which a wide peat bog system developed throughout many years (~ 1500 ha).

Since the end of XVII th century, drainage and agricultural use (grassland and barley), as well as industrial exploitation of peat gradually developed. At present the peat bog only covers around 10 % of its initial extent.

The need for protection of this peat bog relict was emphasized by a drainage upgrading project. This lead to a multidisciplinary study involving biologists, agronomists and hydrologists.

In the interface areas between agricultural land and peat bogs, soil presents quite degraded peat layers 2 meters deep. From various measurements (pumping tests, augerhole method, laboratory) hydraulic conductivity is equal to about 10^{-6} m/s and effective porosity is in the range of 20 % (Soutter 1992).

Figure 6 depicts the extreme and average elevations of the watertable along a transect crossing the agricultural land and the peat bog, as revealed by weekly observations over two years. The particularity of this transect lies in the presence of an old drain at short distance from the edge of the peat bog. It can be seen that the average lateral drawdown effect of the drain remains smaller than 8 meters (e.g. up to piezometer B5) and that it can exceptionally reach an extent of 15 to 20 meters (e.g. up to piezometer B8) in case of prolonged drought, as those of summer 90 and 91.

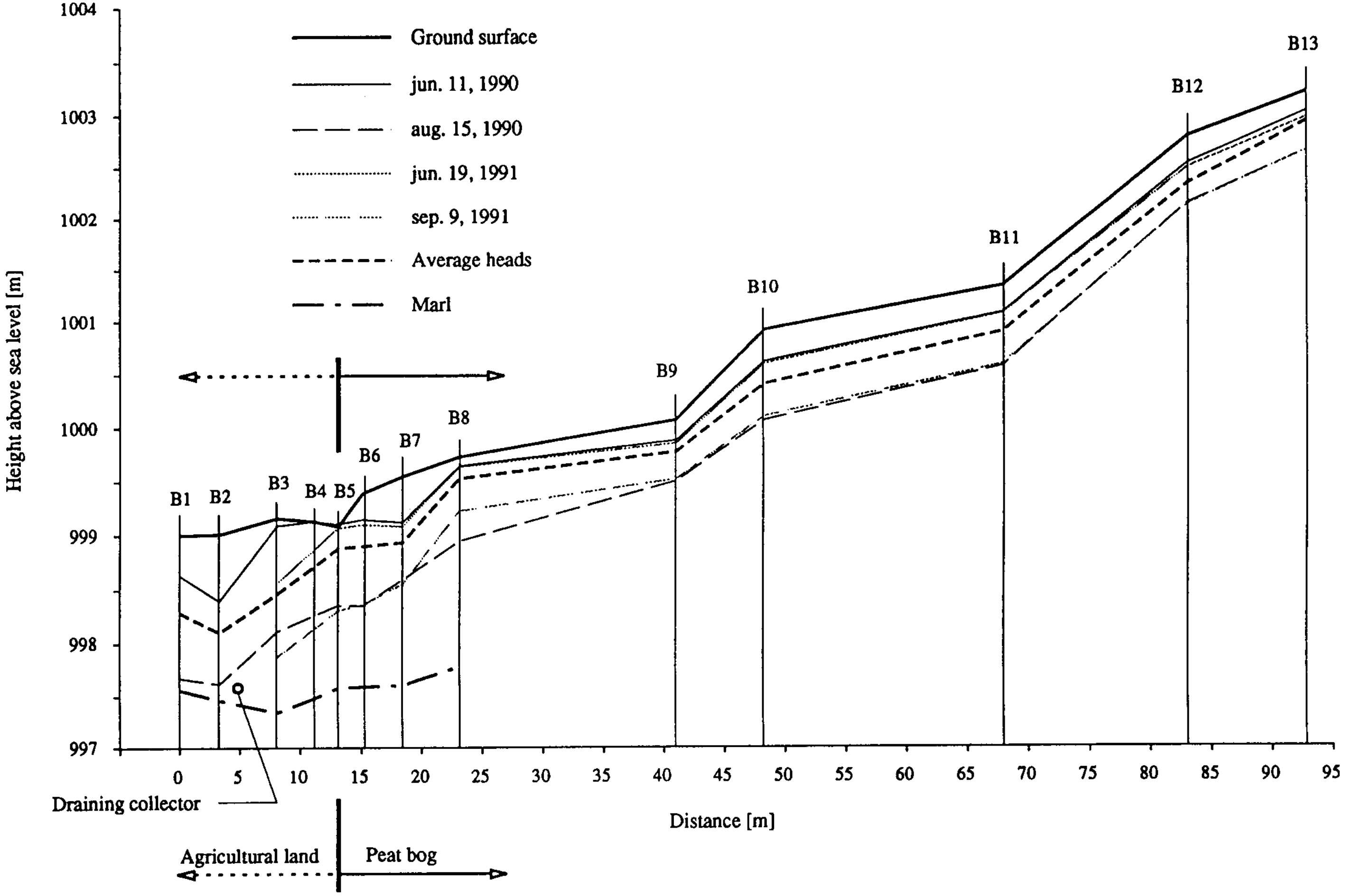


Figure 6. Observed effect of a drain on transect B at Ponts-de-Martel

According to biological recommendations, a critical drawdown level of 30 cm exceeded no more than 30 times a year was used for hydrological buffer zone design. Results shown in figure 5 indicate that a design width of 5-6 meters meets the protection criteria. Compared with the values derived from field observations (figure 6), the proposed (X, R) conditions do not seem conservative enough. However, taking into account a certain margin of error on the estimation of hydraulic conductivity the use of these criteria would lead a design width of the order of 10 meters, thus matching field observations.

Further applications and validations of the proposed method should allow to improve the choice of protection criteria.

Nevertheless, attention should be paid to the fact that if such a method gives some insights into the hydrological aspects of the problem, the overall design of buffer zones also has to fulfill other constraints for which no accurate design method exists.

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SIMPLE MODELS TO PREDICT FIELD SOIL WATER REGIMES IN THE PRESENCE OF DITCH WATER LEVELS MANAGED FOR ENVIRONMENTAL AIMS

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ABSTRACT. Later levels in drainage ditches are frequently manipulated to achieve environmental ends, particularly the preservation and creation of wetland habitats. However, it is by no means clear that the ditch levels will always be translated into the required field water levels. A simple model is used which uses a balance approach to investigate the relationships between the ditch and field water levels in a small catchment. For homogenous soils, very simple drainage equations are adequate to describe the flux between the field and the ditches. Water movement between the field and ditch can either be positive (drainage) or negative (recharge). Various options for the modelling of the behaviour of the ditch outlet are available, and include the calculation of discharge over a control structure, or the imposition of externally defined water tables. Possible extensions to the model which are discussed include (a) the influence of within-field pipe drainage (b) the modelling of non-uniform soil parameters (c) the estimation of the extent of surface flooding within fields, and (d) the estimation of soil surface strength in relation to bird feeding needs.

Examining a set of results for a test site indicates that where soils have high conductivities, then it is possible to control field water tables, but at the cost of a continued use of water in the summer months to meet evaporative demand. However, similar levels of control are not easily achieved for low conductivity soils, in which the rate of movement between ditch and field centre is slow, and the field centres continue to dry out due to evaporative water use. The results of the model are discussed in relation to the management of Environmentally Sensitive Areas in UK.

RESUME. *Les niveaux d'eau dans les collecteurs de drainage sont souvent utilisés à des fins environnementales, particulièrement pour la préservation et la création d'habitats dans les zones humides. Mais il n'est pas évident du tout que certains niveaux dans le collecteur signifient toujours des niveaux d'eau adéquats dans le terrain. On utilise un modèle simple, qui fait appel à une méthode d'équilibrage, pour étudier les relations existant entre les niveaux d'eau dans le collecteur et les niveaux d'eau dans le terrain, dans une petite zone de captage. Pour les sols homogènes, des équations de drainage très simples conviennent pour décrire la circulation entre le terrain et les collecteurs. Le mouvement de l'eau entre le champ et le collecteur peut être soit positif (drainage), soit négatif (remplissage). Diverses options permettent de modéliser le comportement de la sortie au niveau du collecteur, notamment le calcul de l'écoulement sur une structure témoin, ou l'imposition de nappes phréatiques définies extérieurement. Des développements éventuels du modèle sont abordés à savoir (a) l'influence du drainage par tuyaux dans le terrain (b) la modélisation de paramètres de sols non uniformes (c) l'estimation de l'importance de la submersion de surface (d) l'estimation de la densité de surface du sol en ce qui concerne les besoins alimentaires des oiseaux.*

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En examinant un ensemble de résultats provenant d'un test sur le terrain, on constate que lorsque les conductivités des sols sont élevées, il est possible de contrôler les nappes phréatiques dans les terrains, au prix cependant d'une utilisation continue d'eau pendant les mois d'été, pour répondre au besoin d'évaporation. Mais il n'est pas facile d'atteindre des niveaux de contrôle similaires dans les sols de faible conductivité, dans lesquels la vitesse de circulation entre le collecteur et la partie centrale du terrain est faible, la partie centrale du terrain continuant de se dessécher dû à l'utilisation de l'eau d'évaporation. Les résultats du modèle sont discutés relativement à la gestion des Zones Sensibles du Point de Vue de l'Environnement (ESAs) au Royaume-Uni.

INTRODUCTION

In contrast to the recent past in which wetlands were considered prime candidates for agricultural reclamation and improvement, much interest has now focused on the preservation of wetland areas (Maltby 1986). In addition, steps are being taken to actively re-create the wetlands that have been lost, in an attempt both to retain the specific wetland habitat and to increase landscape diversity. Critical to preservation and recreation of wetlands is the deliberate manipulation of water levels, either maintaining existing regimes or creating regimes to meet specific objectives. In lowland Britain, there are few, if any, sites where the natural water regime has been completely unaffected by agricultural intervention either for flood protection or for agricultural improvement.

Although the techniques for water management are technically simple, involving the manipulation of inflow and outflow water levels, it is by no means clear that such actions will always be translated into the desired effects. In particular, it is uncertain that the procedure of setting ditch levels will always be translated into the required soil water regimes. The models discussed in this paper are designed to test the effects of specified ditch management options on the water levels achieved in the field.

MODEL APPROACH

For simple situations, water levels in the field can be calculated from a consideration of the water balance:

$$M_t = M_{t-1} + (R - ET - Q_d) / f \qquad (1)$$

where the water elevation in the field on day t is M_t, R is the rainfall, ET is evapotranspiration, Q_d is the discharge through the drainage systems and f is the relevant porosity. Normally f, defined as the specific yield, is approximated by the drainable porosity of the soil, but where the water level is above the soil surface, then f becomes unity.

Sequences of rainfall and evaporation data are normally available from meteorological sources, so prediction of the soil water regime requires estimates of the flux through the drainage system. For simple soils and geometrically regular situations, this can be calculated from any one of the drainage equations. For soils of uniform hydraulic conductivity, K, drained by parallel ditches at spacing L, the Donnan drainage equation (ILRI, 1973) can be easily used to predict the drainage fluxes:

$$Q_d = 4K\left(M_t^2 - D_t^2\right) / L^2 \qquad (2)$$

where D_t is the level in the ditches at time t.

It should be noted that the flux between ditch and field, Q_d can be in either direction, and therefore includes both drainage (Q_d is positive) and recharge (Q_d is negative). The model can therefore represent both the winter and summer phases of operation.

It should also be noted that the assumptions in equation (1) are that evaporation taken from the profile results in a direct fall of the water table. This is in fact a simplification, as in practice the effect is to remove water from the whole profile. However, the solutions of the equations of unsaturated flow (the Richard's equation) are notoriously difficult, and impose large demands on the computing resources. For this reason the simplified representation is adopted.

If the level in the ditches is input into the model as an externally constrained set of values, then the water balance can then be solved directly. This simple situation is the most basic representation of the model, whose use has been described by Armstrong (1993). However, it also possible to apply the same budgeting procedure to the levels in the ditches. We may thus define a second balance:

$$D_t = D_{t-1} + Q_d / D_f - (Q - P + I) / D_a \qquad (3)$$

where

D_t is the ditch level at day t,
Q_d is the discharge from the field to the ditches defined by (2) or some alternative,
Q is the discharge from the ditch system,
P is the pumping rate if applicable,
I is the inflow into the catchment,
D_a is the area of ditch within the catchment and
D_f is the area of the catchment divided by ditch area.

It should be noted that such a simple model makes no allowance for variation in ditch levels within the catchment, and is therefore applicable only to small catchments where hydraulic gradients are small.

The implementation of the model then depends on the definition of the components of the system that are to be included. At present, the following options have been programmed:

(1) *Pumping*. The pumping regime is defined by stating that pumping starts whenever the ditch level, D_t, exceeds a specified level. At this point a fixed volume is pumped from the ditch system. This pump operation is implemented only once in any one day, and corresponds with the practice in most pumped areas of lowland Britain.

(2) *Discharge* over a control structure. Usually the rate of outflow can be estimated using the information about ditch level and the dimensions of the control structure. The water height over a weir can be defined as the difference between its control level and the ditch level, and the discharge calculated from the Francis formula, or similar for other shaped weirs.

MODEL EXTENSIONS

The model as it has been described, provides a simple balance approach which enables the user to examine the effects of adopting various actions, such as the imposition of ditch levels, the setting of control structure levels, or the direct import of water. However, the model is also capable of development should the application require. A number of possible extensions have also been suggested, and the relevant programming has been undertaken. These options are available as extensions to the model.

The influence of pipe drainage

So far, the flux between the field and the ditch has been assumed to be governed by the Donnan equation (2) for parallel ditches. However, fields may also have pipe drainage systems within them. It is thus possible to define a second component to the flux between field and ditch, due to pipe drainage. This adds a further term to the flux, Q_d, in equations (1) and (3).

Pipe drainage operates only when the water table in the field is above the pipe, and the water level in the ditch is below the pipe height, so providing a free outfall. The flux through the drain can then be calculated simply using for example the Hooghoudt drain spacing equation (ILRI 1973). The only additional parameters therefore, are the depth and spacing of the pipe systems.

Non uniform soil parameters

The assumption of a vertically homogenous soil is commonly used for drainage modelling, but does have severe limitations. It is frequently observed that the hydraulic conductivity of soils decreases with depth. Solutions for the flux through drains in soils in which the hydraulic conductivity varies continuously as a function of depth (or height above the drain) are given by Youngs (1965), based on the Girinsky seepage potential. He showed that it is possible to define drainage equations for depth dependent variations in hydraulic conductivity. For ditch drains spaced 2D apart and sunk to an impermeable floor in a soil whose hydraulic conductivity K(z) varies with the height z above the impermeable floor the flux, q, is given by the inequality:

$$\int_{Hw}^{Hm}\left[\int_{0}^{H} K(z)dz\right]dH > \frac{qD^2}{2} > \int_{Hw}^{Hm}\left[\int_{0}^{H} K(z)dz\right]dH - \int_{0}^{Hm}\left[\int_{z}^{Hm} \frac{q}{K(z)}dz\right]K(z)dz \qquad (4)$$

where Hw is the height of water in the ditches, and Hm is the maximum water table height, at mid drain spacing. For soils in which the hydraulic conductivity decreases with depth, the left hand side of this inequality, which is the Girinsky potential, is not so different from the right hand side and thus can be taken as the drainage equation to be used in equation.(3). Guyon (1980), in an analysis similar to that used by Youngs (1965), considered an "equivalent hydraulic conductivity" of a soil that varies with depth, indicating how this concept might be used in falling water table drainage situations.

A particular form of K(z), that is suggested by measurements such as those of Youngs & Goss (1988), and which appears to have considerable generality, is an exponential decrease in conductivity. This has been suggested both for clay soils (Armstrong et al 1991), but also for alluvial soils (see section 4, below), and is suggested for data from peat soil. If this is written as:

$$K(z) = K_0 e^{\beta z} \tag{5}$$

where K_0 is the hydraulic conductivity of the saturated soil at z=0, and β is a constant. The left hand side of inequality [4] with H_W=0 then yields:

$$q = 2K_0\left[\left(e^{\beta Hm}-1\right)/\beta D-\left(\frac{Hm}{D}\right)\right]/\beta D \tag{6}$$

This can be used simply in equation [2], as can similar equations developed for other depth variations of hydraulic conductivity, in a numerical procedure to obtain the water table height at successive increments of time.

However, the solutions require further modification where used for ditch modelling, because the integration of equation [4] to give the simple forms of equation [6] in Youngs (1965) assume empty ditches, i.e. Hw=0. The considerations of water filled ditches however requires the change in the integration limits in [4]. For the case of hydraulic conductivity described by equation [5] the flux is given by the difference between the flux with water table height at Hm and the ditches empty and the corresponding flux with the water table at height Hw and the ditches empty. After simplification and re-arrangement, this yields a new equation:

$$q = 2K_0\left[e^{\beta Hm}-e^{\beta Hw}-\beta Hm+\beta Hw\right]/\beta^2 D^2 \qquad [7]$$

which can be easily included in the model.

Estimation of surface flooding

The creation of the ecological requirements of some bird populations (which are often taken as critical indicators) requires the deliberate maintenance of partially flooded areas (Tickner & Evans, 1991). If the water table is assumed to be nearly flat, it is possible to estimate the percentage flooded area from the intersection of the estimated water table position and the observed distribution of topographic heights. For this reason it is often essential to have some measure of the microtopographic roughness of the area modelled, ideally as a cumulative frequency curve. Collection of these data requires measurement not only of the gross topographic features of the site, but also measurement of the microtopography. For this reason we have found that best information is given by a series of closely measured transects, which give sample estimates for the whole field, rather than systematic surveys which tend to define only the macrotopographic features.

However, it is also possible to consider the shape of the water table in the field. The simple analyses considered so far have all assumed that the estimation of the water table height in the centre of the field (i.e. at mid-drain spacing) is adequate to characterise the soil water regime. However, it is possible to calculate the form of the water table, either in two dimensions or in three (Youngs et al 1989) and so estimate the soil water regime at other locations within the field.

Estimation of soil surface strength

The estimation of soil surface strength is often required to estimate bird feeding needs. It has been suggested that the ability of birds to probe the soil for food is a major factor in the choice of sites for breeding. The penetration resistance of the soil is a measure of the difficulty that a bird might be expected to have in feeding.

Normally, the soil surface strength can be estimated from the water table position. There is for many soils a relatively well defined relationship between soil strength and water content. As a first approximation, soil water content at the surface is also correlated with the water table depth from the surface, so a relationship between strength and water table can be inferred and is observed for many soils. This relationship cannot, however, be established from a priori principles, and must be calibrated from field observation. However, it also observed that in some situations, agricultural management effects, such as soil compaction due to over-intense grazing, can completely mask this relationship.

For work specifically related to bird beak penetration, a special penetrometer has been devised (Green, 1986) and has been used. It records the force required to force a narrow cylinder into the soil a distance of 100 mm, and as such mimics the behaviour of a bird beak. Field data show that this technique yields a good correlation with soil moisture, and can be used to identify areas and times suitable for bird feeding.

TEST RESULTS

The model described above has been used by Armstrong (1993) to examine the ability of ditch management regimes to generate suitable within-field regimes (Figure 1). Although restricted to a theoretical analysis in uniform soils, he was able to show that where the hydraulic conductivity of the soil is high (as in many peat soils) then it is possible to control in-field water levels by setting the ditch water levels high. The model, however, also demonstrated that for the UK, these high water levels required the import of significant quantities of water (in excess of 100 mm per unit area) to meet the evaporative demand that is created by the growing vegetation. By contrast, the same study showed that where soils have a low conductivity (as in some alluvial clays), then it is much more difficult to maintain high water tables in the fields, because of the difficulty in moving water through such soils. It was shown that the water regime in such soils is dominated by the summer evaporative demand, and that recharge through the drains is only a very small amount.

The model was further used to examine the effects of water management regimes in the Broads Environmentally Sensitive Area (ESA) (MAFF 1989). This is an area where grazing coastal marshes below mean sea level are being maintained in a wet condition to retain their landscape value and to enhance their ecological value. Water levels are maintained by a series of ditches controlled by sluices, and these are set to maintain a target water level of 45 cm below field surface level. Detailed monitoring of the water levels in the ditches and in the fields is undertaken (MAFF 1991).

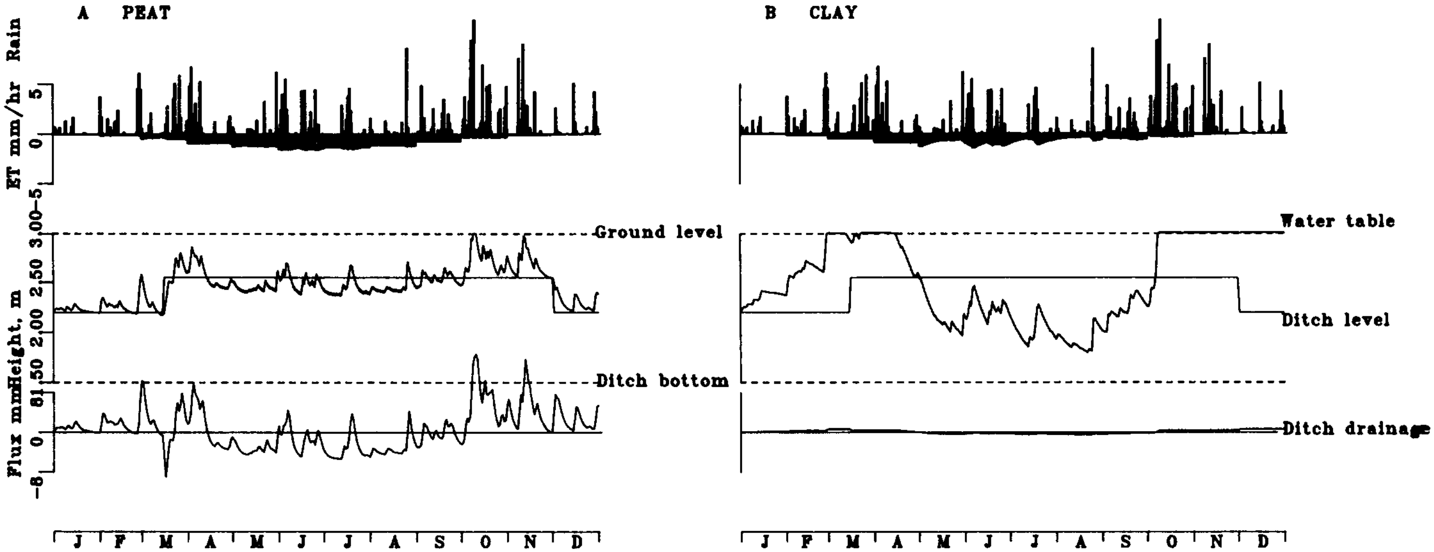

Figure 1. Rainfall, ditch regimes and soil water regimes for two soils types (high conductivity peat and low conductivity clay) for a ditch regimes representing the optimum bird breeding conditions as defined in Armstrong (1993).

The soil of the site is an alluvial clay, with very well developed structure near the surface, becoming massive and impermeable at depths greater than 1.5m. Hydraulic conductivity data collected using the auger hole method showed a strong decrease with depth. These data were fitted to the exponential distribution using linear regression techniques. The depth dependent model, equation (7), was thus used to predict the actual water tables in response to the ditch levels that were observed (Figure 2) for the year 1991. The ditch levels were intended to maintain high levels in the bird breeding season (March to June), but were allowed to fall later in the summer because of a severe water shortage in the area. Whereas the area is normally kept dry by pumping, it was necessary to import water to meet cattle drinking needs, and it was not possible to maintain the ditch levels at the targets. The model results show a fall in the mid-field water table, away from the ditch margin in the summer months, in response to the evaporative demand. This results in a flow from the ditch to the field for most of the summer, which is however restricted by the low conductivity of the subsoil. However, at other times, particularly in the autumn, the dominant water movement was from the field to the drain in response to heavy rainfall events.

The predicted water tables can be compared to those observed in the fields. Figure 3 records the ditch levels, the predicted water tables, and the water tables observed in the field centre by a single water level recorder, and mean water levels recorded in replicate dipwells at 18 separate occasions. These show excellent agreement between the model and the observation. The only major discrepancy is with the large rainfall event at the end of September. Field observations suggested that much of this rain ran off the fields because of infiltration limitations, and did not enter the soil. This process is not considered in the model, and the short period of mis-match between model and observation was not considered to be sufficient reason to reject the model.

On the same set of fields, measurements of microtopography had been undertaken using a 1m spaced transect from corner to corner to give detailed information. The cumulative distribution of height values was then used to infer the degree of surface flooding at any time. This is an important variable because of the importance of some flooded areas for the successful breeding of some important bird species (Tickner & Evans 1991). From Figure 3 it can be seen that some areas remain flooded until the end of May, but that apart from the single large rainfall event in September, flooding was never more than 10% of the area of the land. This observation was in accord with visual assessment of the state of the land made by the site recorder.

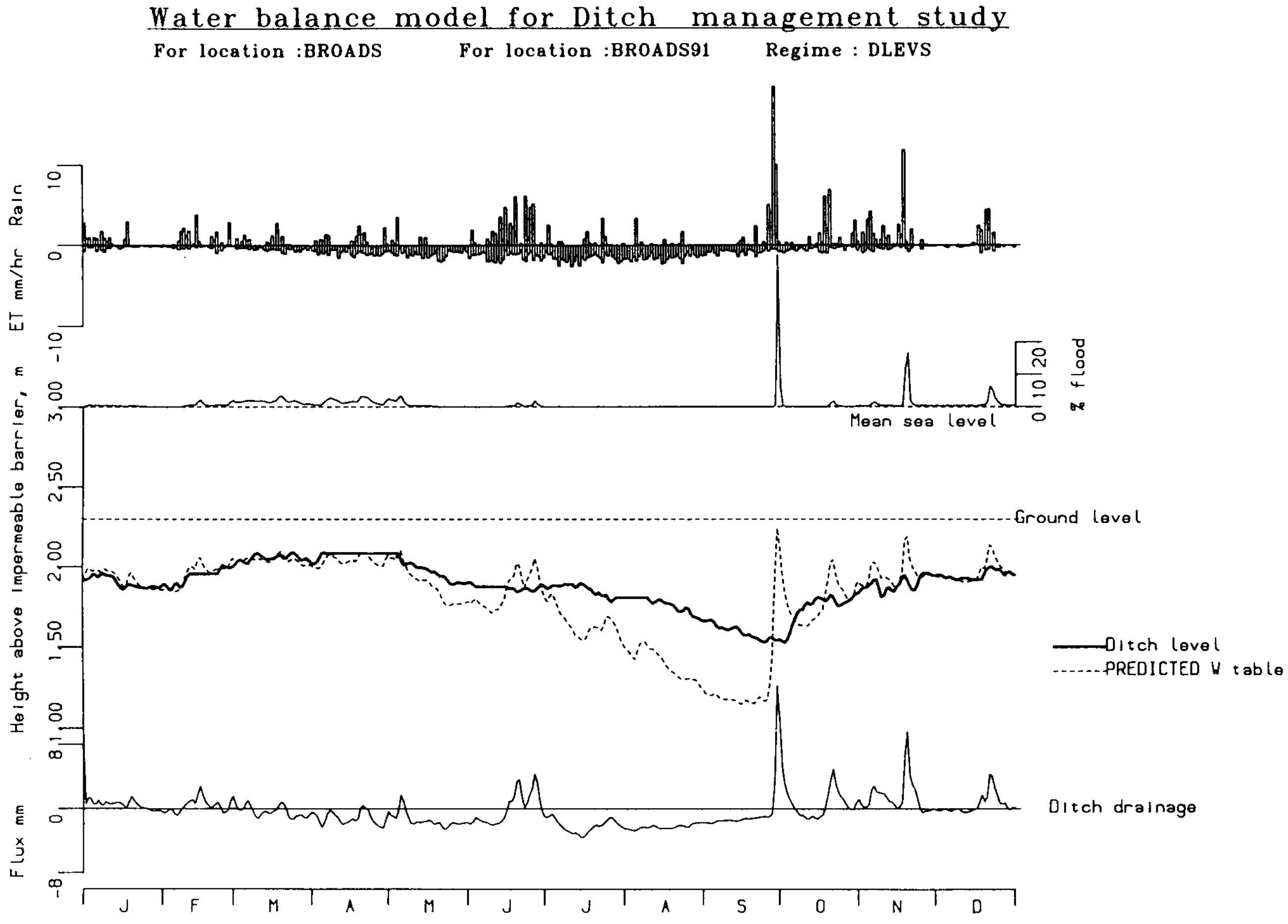

Figure 2. Model predictions for the Broads ESA for the year 1991. Data shown are, from to bottom of the diagram: rainfall and potential evapotranspiration inputs; percentage flooded area, ditch and mid-field water levels; and rates of discharge between ditch and field.

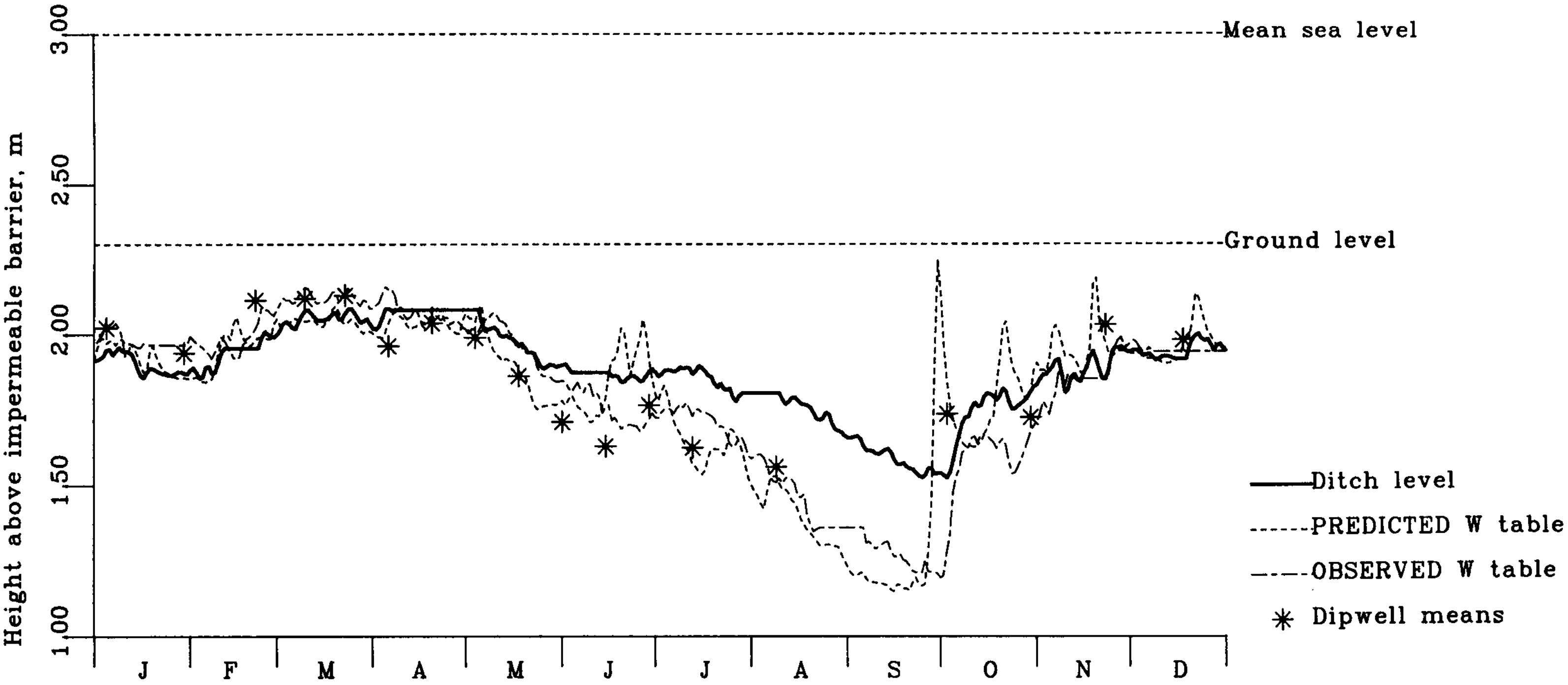

Figure 3. Comparison between observed and predicted field water levels from the Broads ESA. Observed water levels are from a single continuous in-field meter and the mean of multiple dipwells.

DISCUSSION

This paper has shown how a very simple budget model can be used to estimate the soil water regimes and ditch regimes in small catchments where the ditch levels are being manipulated.

The results from the model have indicated the difficulty in maintaining wetness through sub-irrigation. For low conductivity soils it may be nearly impossible because of the inability of the soil to transmit water from the ditches to the field centre. For high conductivity soils, the volumes of water required may be large for extensive reserves. The model has shown how these issues can be addressed at the planning stage, and how they may take into account the ability of the situation to meet ecological aims in terms of surface water flooding.

The overall philosophy behind the development of the computer programs has been that each application is unique. Consequently, no single, multi-option model has been built. Rather the same model has been used throughout to provide a structure, while for application the necessary components have been built into the computer code used. In this way a library of relevant components has been developed.

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MATHEMATICAL MODEL FOR SIMULATION OF GROUNDWATER IN THE REGION OF LACUL MORII

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ABSTRACT. The achievement of the **Lacul Morii storage** lake for rivers training through the city of Bucharest will imply important changes in the underground water regime in this area. In order that the social-economical objectives should not be negatively affected by those changes, we have designed and constructed a perimetral drainage system which is aimed to maintain the underground water levels at the natural regimé elevations. A mathematical model for simulation of groundwater regimes in the region of **Lacul Morii was used** during the stage of designing. The paper presents the modelling of the aquiferous, the mathematical model calibration and the modified states of aquiferous simulation. It proves the capacity of the mathematical model to reflect accurately the groundwater regime **from the Lacul Morii** water storage zone.

RESUME. *L'accumulation de **Lacul Horii**, exécutée sur la Rivière de Dimbovita - le principal cours d'eau arrosant la ville de Bucarest la capitale de la **Roumanie** - est située a l'entrée de la rivière a travers une zone bucarestoise ayant une forte densité de constructions.*

L'accumulation a un volume utile d'environ 30 mil.mc, une superficie d'environ 260 ha et s'étend sur 3 km le long du cours de la rivière.

En régime naturel, le principal draineur des eaux souterraines de la zone ou l'accumulation est construite etait le lit profond de Dimbovita.

La réalisation de l'accumulation produit la modification du régime d'écoulement des eaux souterraines et, par la suite, le danger d'une importante hausse du niveau de celles-ci. La hausse a une importante portée sur les nombreux objectifs socio-économiques du voisinage qu'elle va influencer d'une façon nuisible.

*La prévision du régime des eaux souterraines sous l'influence de l'accumulation de **Lacul Morii** a été réalisée au moyen d'un modèle mathématique.*

Celui-ci, se basant sur l'intégration de l'équation générale du mouvement de l'eau a travers les milieux poreux par la méthode des éléments finis a admis comme point de départ l'hypothèse d'un écoulement permanent plan-horizontal.

Le même modèle a établi les paramètres principaux du système de drainage à exécuter sur le contour de l'accumulation dans le but de protéger les objectifs socio-économiques de la zone. Le système de drainage de contour a été partiellement mis en service en 1988.

15th International Congress of ICID, The Hague - *15ème Congrès International de la CIID, La Haye.*
Workshop on Subsurface Drainage Simulations Models - *Atelier sur les modèles de simulation du drainage.*
ICID - CIID, CEMAGREF, 1993, 159-170. Printed in France.

Les mesures effectués sur le terrain - comparées à la simulation sur le modèle mathématique du fonctionnement partiel du système de drainage - ont mis en évidence le fait que le modèle a rendu une image exacte du phénomène naturel.

INTRODUCTION

The Lacul Morii water storage, carried out on the Dimbo - vita river, the main natural water course which passes through Bucharest city, the capital of Romania, is located at the entrance of the river into the town, in a very dense built zone (Fig. 1). Except for a very small area used for agriculture, around the lake there are many social-economic objectives namely: factories, blocks of flats with 8-10 levels, research institutes and the underground buildings of the Bucharest tube, Figure2.

Under natural regime the zone of the water storage was drained mainly by the Dimbovita river course, whose annual average levels on this sector is between (74-75)m.B.S.(a).The carrying out of the water storage, having the normal retention level 85 (b)m.B.S.,was expected to modify the natural regime of the groundwater from the zone, rising thus their level in the neighbouring areas.In order to protect the social-economic objectives from the zone against the possible damages caused by this phenomenon a drainage system on the contour of the water storage was decided to be carried out. The necessity of the drainage system and its parametres were established based on a groundwater prognosy, study carried out using mathematical modelling.

GENERAL DATA

Lacul Morii is a plain water storage carried out by a wire concrete dam. The lake is limited on the left bank by an earth dike about 10 m high and on the right bank by a high terrace whose average level is 90,0 m.B.S. (Fig.. 2 and 3).

The surface of the lake is about 270 ha and its volume about 15 mil. cubic metres. the water storage improves the flow and the levels of the Dimbovita river in zone of Bucharest.

The earth dike is watertighted by a concrete pitching continuing in the foundation ground by a self -strenghted bentonite mud screen, Figure 3.

The high terrace from the right bank is not watertight. It is only protected by a permeable concrete pitching against the erosion caused by the waves (Fig. 3).

From the geological point of view the zone **of the Lacul Morii** water storage is characterised by a stratified and very heterogeneous structure, Figure 3. From the surface, up to depths of about 250 m, layers of Quaternary age developed. In succesion there is a marl complex of Pleistocene age, which constitutes an impermeable barrier between the deep,under steam aquiferous and the superior aquiferous.

The superior aquiferous complex is characterized by the existance of more permeable layers alternating with impermeable layers. The hydraulic conductivity coefficient of the permeable superior layers, made of fine sand, varies between (30-50)m/day.

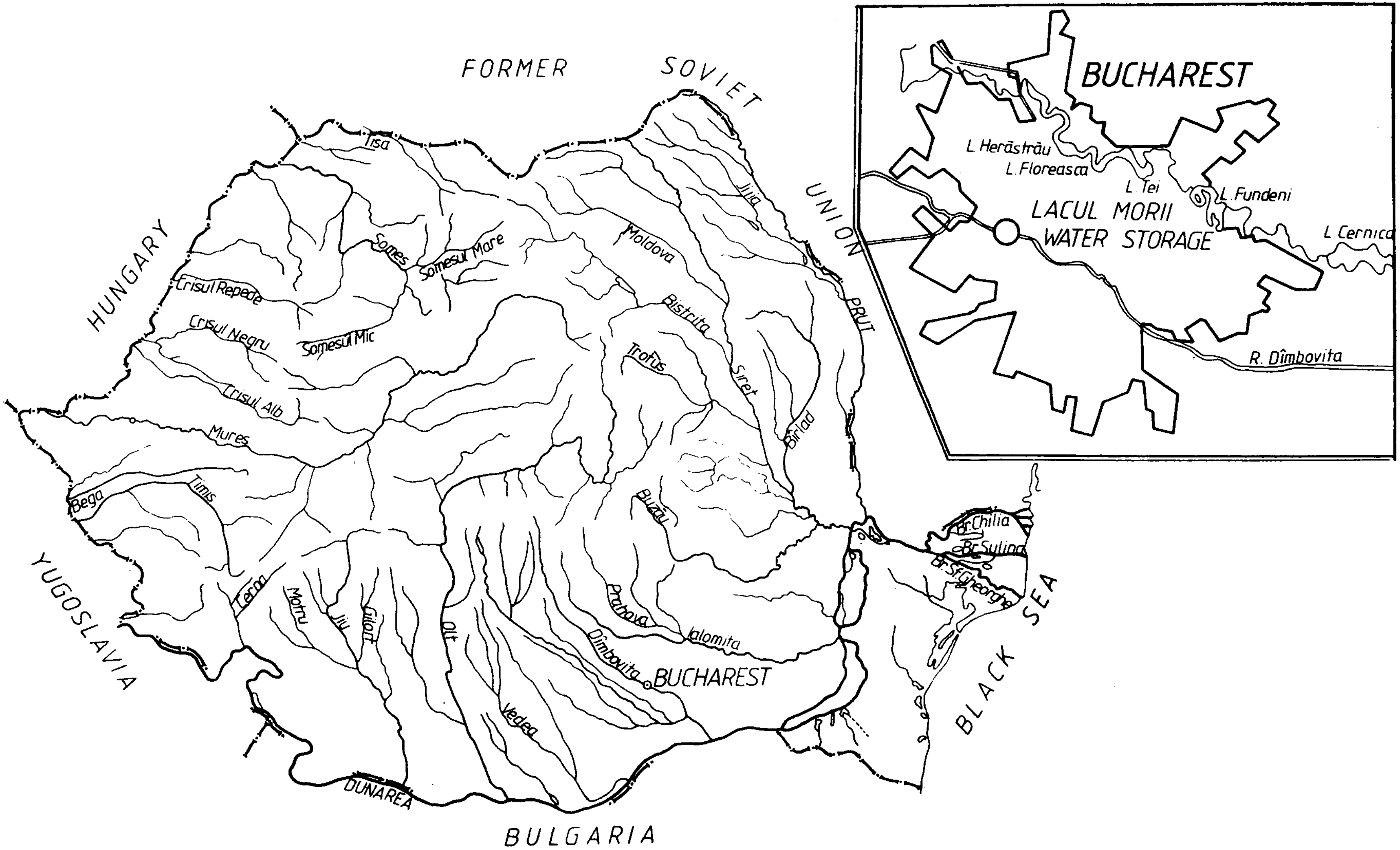

Figure 1. The site of Lacul Morii water storage

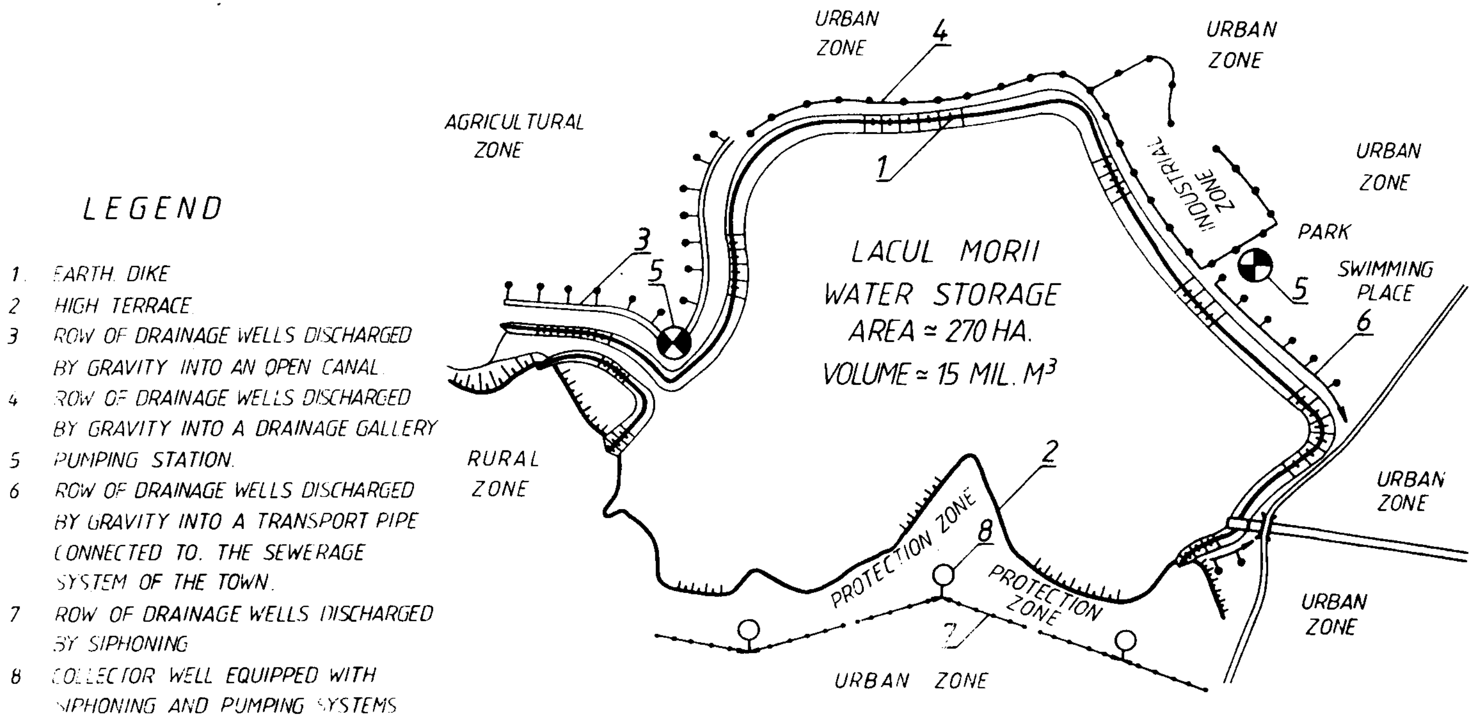

Figure 2. General view of the Lacul Morii water storage

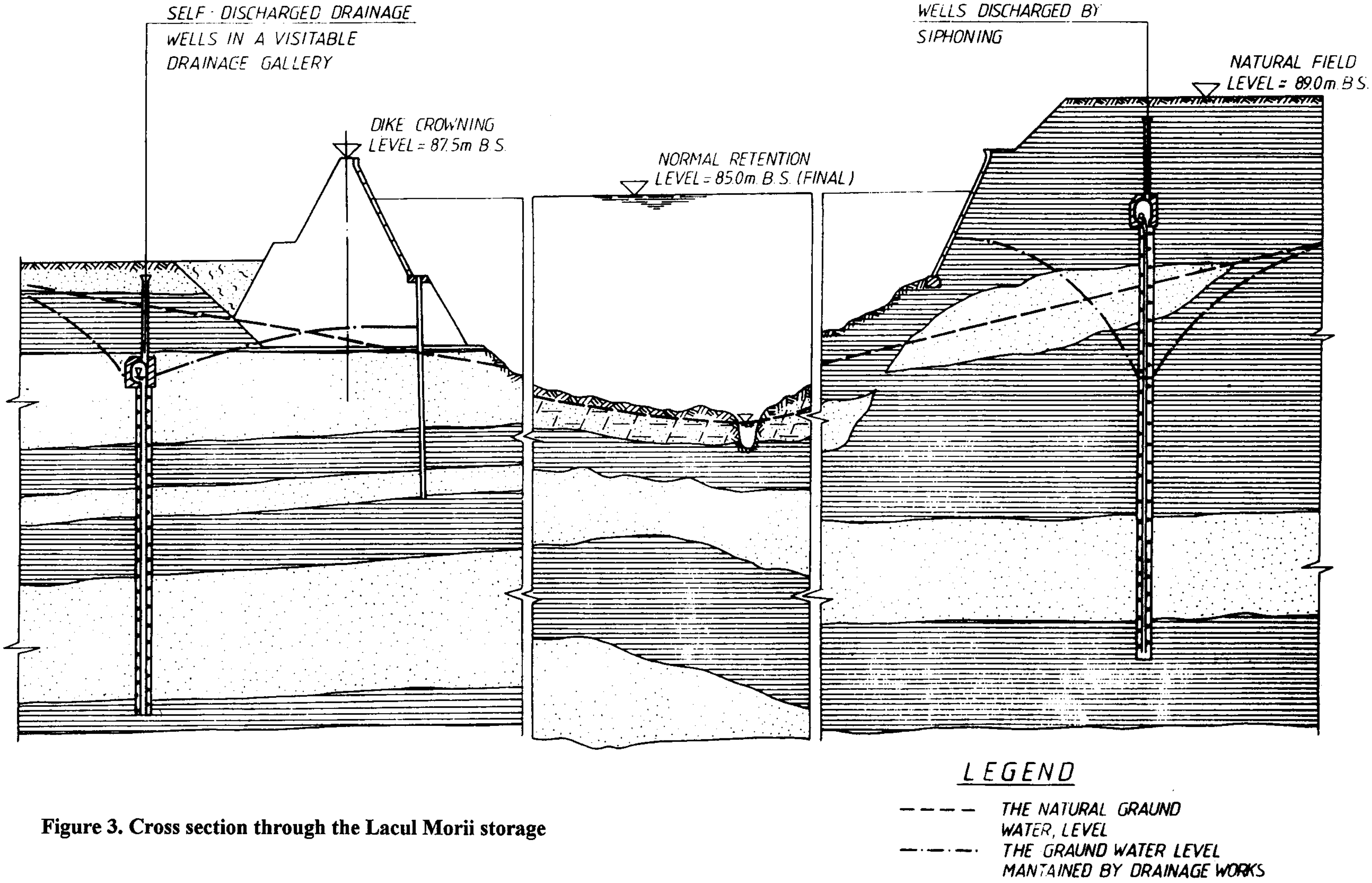

Figure 3. Cross section through the Lacul Morii storage

The deepeest permeable layers made of a mixture of fine sand coarse sand and gravel has a hydraulic conductivity coefficient between (70-100)m/day. The hydraulic conductivity coefficient of the impermeable layers made of a mixture of clay and dust, varies between (70-100) m/day.These layers are discontinuous favouring the space hydraulic communication among the permeable layers. The transmissivity of the entire aquiferous complex was estimated at about (75-100)m2/day in the high terrace zone and (200-250)m/day in the plain zone. **(Mihnea and all, 1989**)

THE MODELLING OF THE AQUIFEROUS

The forecasting study was carried out by an existing calculation program which can solve the general equation of the groundwater motion through porous saturated media by means of F.E.M. (c).

The basic hypotheses allowed in calculus were:steady-state, plan - horizontal motion.

The motion domain of the groundwater was discretised by a 526 F.E. (d) network with 512 nodes, Figure 4.

The dimension and the structure of the F.E. network took into account the following criteria:

- constructive characteristics of the water storage;
- hydrogeological characteristics of the grounds;
- ampleness of the existing field studies;
- minimisation of the calculus time;
- to facilitate the automatic generation, in the highest possible share, of the F.E. network **(Roy K.C. and all 1992)**

Checking the shape of the F.E. network it can be easily noted that it allows the modelling of natural elements from the zone(the course of the Dimbovita river,the high terrace, a.s.o.) and the constructive elements of the water storage (the lake contour, the pheripherical drainage, etc.).

The lateral limits of the model are arbitrarily chosen and they have been imposed by the importance of the existing field studies, Figure 5.

The F.E. transmissivity was 75 m /day in the high terrace zone and 200 m^2/day in the plain zone.

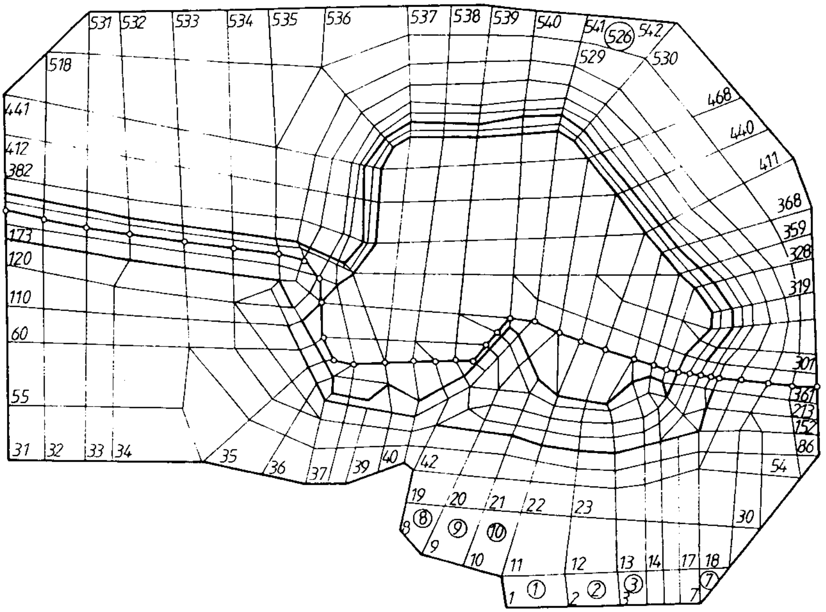

Figure 4. The discretisation of the groundwater motion domain from Lacul Morii water storage neighbourhood by a finite elemnts network

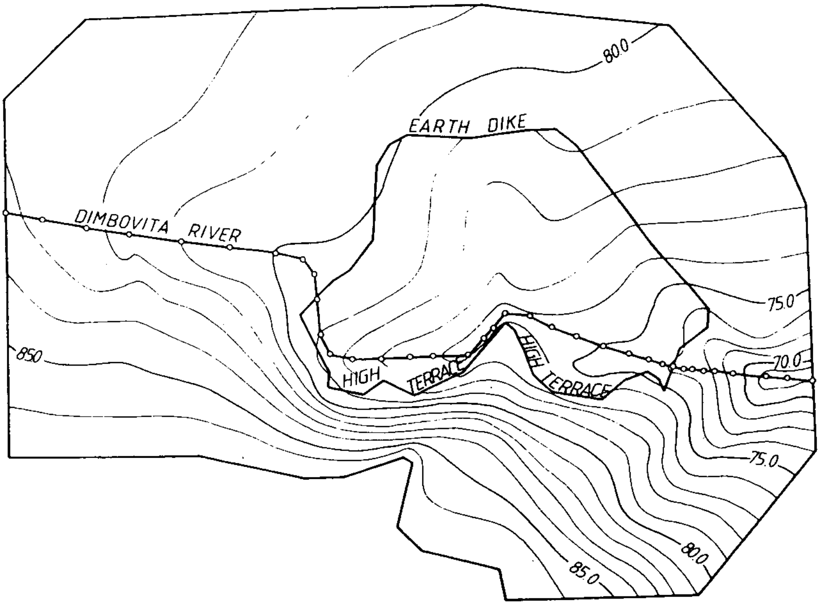

Figure 5. Hydroizophypses in the Lacul Morii water storage zone - natural regime

THE MATHEMATICAL MODEL CALIBRATION

The calibration of the model was made on the base of the multiannual hydroisohypses registered in the natural regime FIG. 5. The method of calibration by means of the imposed discharge was used. According to this method the model calibration is carried out in two stages namely:

-**1st stage** - the boundary conditions are entirely of imposed hydraulic head type; in the nodes on the Dimbovita river, the imposed hydraulic head is equal to the multiannual level of the river registred in the natural regime; in the remained nodes the imposed hydraulic head is equal to the multiannual groundwater level according to the registered hydroisohypses; by means of these boundary conditions discharges in all nodes of the F.E. network can be obtained.

- **2nd stage** - the boundary conditions are both of imposed hydraulic head and of imposed discharge type: the previously imposed hydraulic heads in the nodes of Dimbovita river course are maintained; the discharges established previously are imposed in the rest of the nodes; under these boundary conditions, the model reproduces acurately the registered hydroisohypses,proving that it has the capacity to reproduce the natural regime of the groundwater in zone.

THE MODIFIED STATES OF THE AQUIFEROUS SIMULATION

On the calibrated model, two different categories of modified states of the aquiferous have been simulated namely:

a) in the hypothesis of **the Lacul Morii** water storage carrying out without a peripherical drainage and

b) in the hypothesis of the water storage carrying out with a peripherical drainage.

Each of these two above mentioned categories of simulations was analised in more variants:

- with and without suplimentary supply of the aquiferous caused by the water losses from the urbane networks;
- blocking or releasing the nodes from the contour of the model;
- with one or more drainage systems on the water contour;
- with the peripherical drainage at different levels.

The aims of all these simulations were:

- reduction of the model deficienties due to the relative small area around the lake, of the existing field studies;
- analysis on the model of all situations possible to occur during the operation of the water storage;
- determination of the optimal solution for the peripherical drainage system.

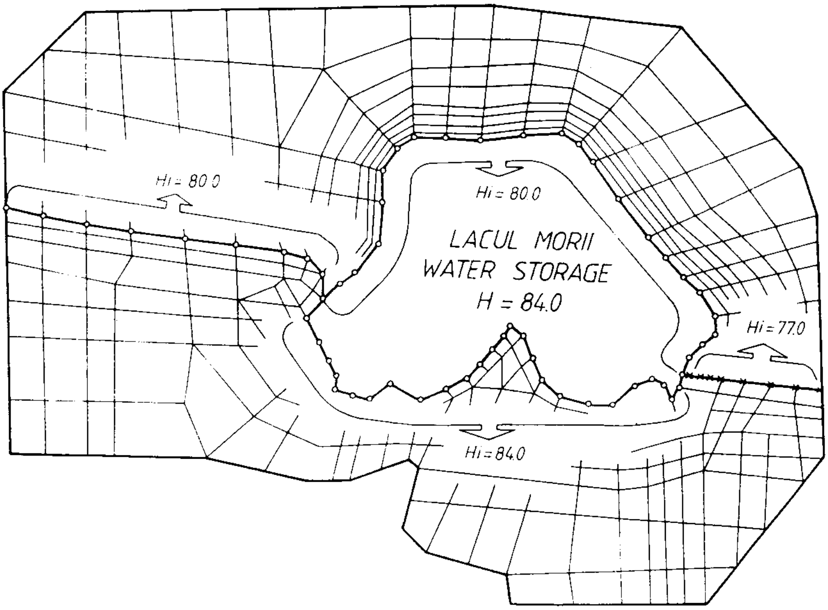

Figure 6. Boundary conditions to simulate the water storage carried out without a peripherical drainage system, Hi - imposed hydraulic head, H - modelled retention level

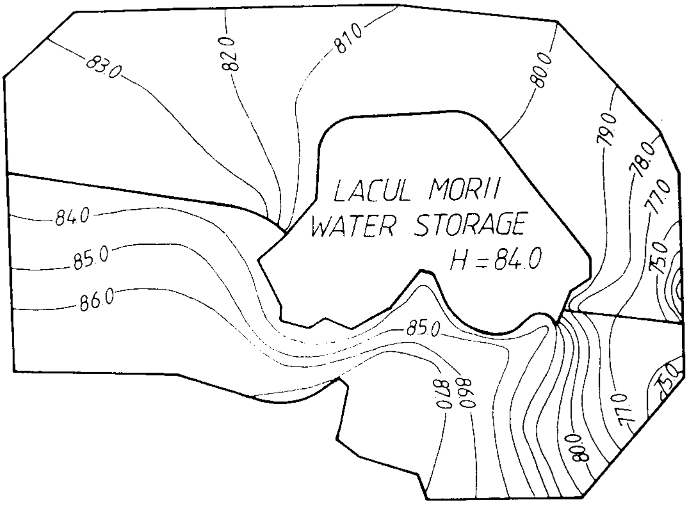

Figure 7. Hydroizohypses for the hypothesis of Lacul Morii storage functionning without a peripherical drainage system, H - modelled retention level

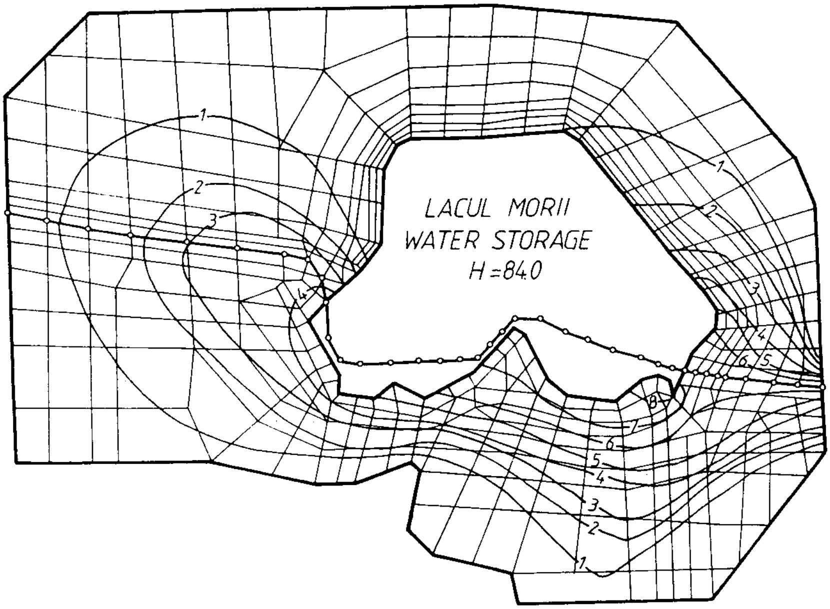

Figure 8. Lines of equal groundwater level rise for the hypothesis of Lacul Morii water storage functionning without a peripherical drainage system, H - modelled retention level

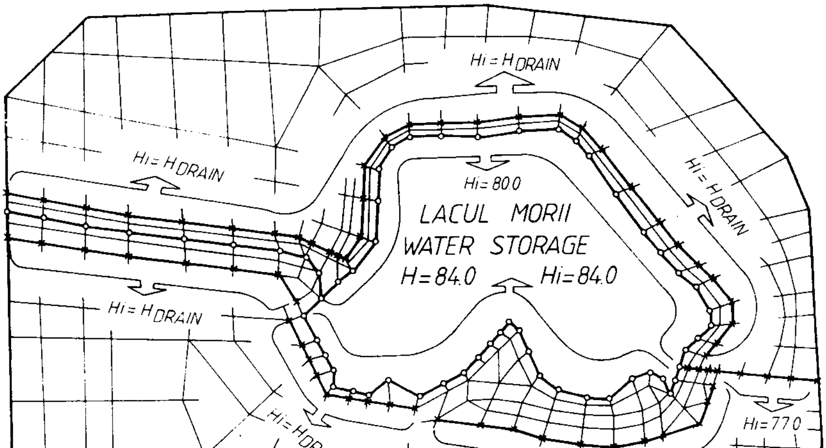

Figure 9. Boundary conditions to simulate the Lacul Morii water storage carried out with a peripherical drainage system, Hi - imposed hydraulic head, H - modelled retention level

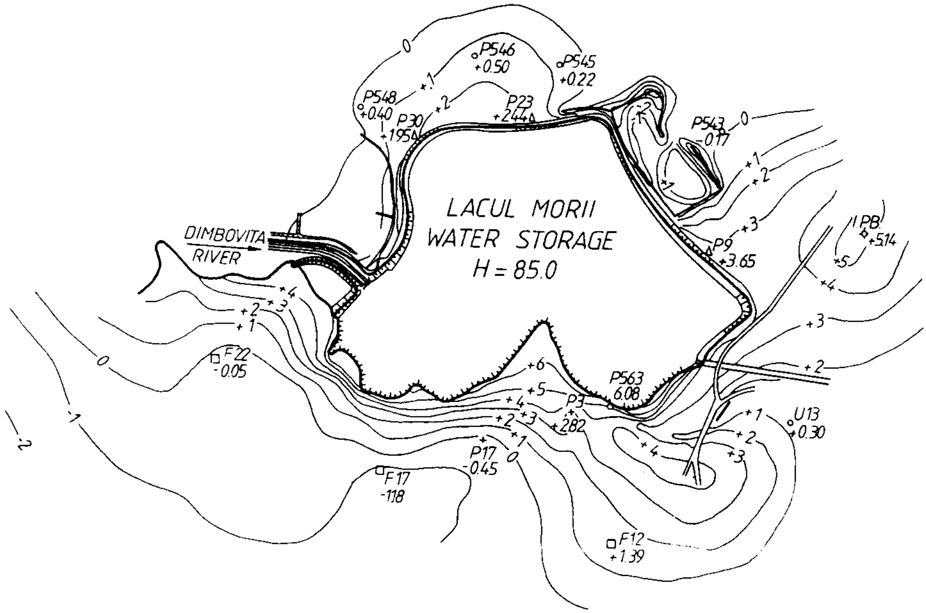

Figure 10. Lines of equal groundwater level rise established by field measurements, H - normal retention level, P.F.U. - piezometers worked out at different building stages

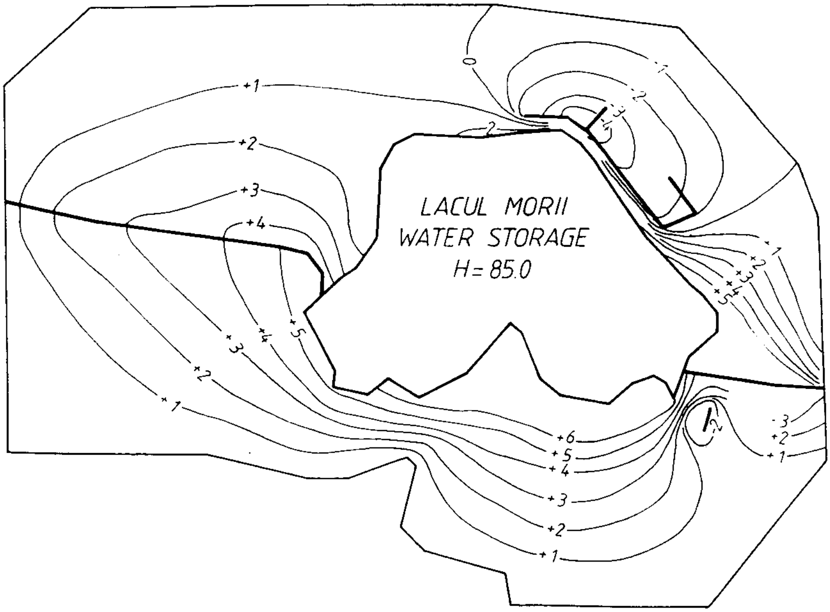

Figure 11. Lines of equal groundwater level rise established by mathematical modelling, H - modelled retention level

The boundary conditions to simulate the water storage without the peripherical drainage (state a), Figure 6 were:

- imposed hydraulic head equal to the normal retention level in the nodes situated on the lake contour from the high terrace zone;
- imposed hydraulic head equal to the normal retention level minus the hydraulic head loss through the watertight elements (about 4,0 m) in the nodes located on the lake contour from the plain zone;
- imposed hydraulic head equal to the average multiannual levels registered on the Dimbovita river in the nodes located on the river course downstream the lake;
- imposed discharges equal to the values esthablished by calibration in all the remained nodes of the *E. F.*- network.

The probable hydraulic heads in the hypothesis of the water storage carrying out without a peripherical drainage, were obtained by means of these boundary conditions. They allowed drawing of hydroisohypses corresponding to these hypothesis, FIG. 7. Lines of equal rising of the groundwater level in the hypothesis of the water storage carrying out without a peripherical drainage, were established by means of the natural hydroisohypses and of those esthablished by modelling, Figure 8.

The boundary conditions to simulate the water storage with a peripherical drainage (state b), are the same with those previously presented (state a) plus imposed hydraulic head in all the nodes from the peripherical drainage beam, Figure 9. The probable hydraulic heads and the discharges collected by the drainage were established by means of these boundary conditions. The hydraulic heads in this case are close to those from the natural regime. The discharges collected by the peripherical drainage vary between the limits (30....200) l/s.km.

Carrying out of the peripherical drainage and its main parameters have been decided on the base of the prognosis study results.

The peripherical drainage system was partially put into operation in 1988. Lines of equal modifying of the groundwater level in **the Lacul Morii** zone under conditions of partially operation of the peripherical drainage system were established by field measurements, Figure 10. They were established by means of the above described mathematical model too, Figure 11. A satisfying similitude of these two categories of lines can be noted. It proves the capacity of the mathematical model to reflect accurately the groundwater regime from **the Lacul Morii** water storage zone. **(Gazdaru and all 1990)**

Similar studies were carried out for other artificial water storages built in Romania in the latest years.

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MODELING FLOW AND TRANPORT IN HETEROGENEOUS, DUAL-POROSITY DRAINED SOILS

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ABSTRACT. A finite element solution of the equations for coupled flow of water and transport of chemicals in slowly permeable soils containing macropores is presented. Two example solutions are presented for the condition of a horizontal soil profile with a drainage ditch. The first is for steady state saturated flow while the second is for transient water flow produced by time varying rainfall. Through these examples it is found that the characteristic leaching time of a chemical from the soil matrix is determined by the rate of transfer of chemical mass between the pore domains. When the rate of transfer is zero, the rate of leaching is greatly retarded compared to the case where the rate of transfer is non zero. The chemical outflow from the macropore domain is very rapid when the rate of transfer is zero, while the chemical outflow is greatly delayed, but increased in magnitude when the rate of chemical transfer is nonzero.

RESUME. *Une solution par éléments finis des équations régissant l'écoulement de l'eau et son influence sur le transport des composés chimiques a l'intérieur de sols à perméabilité faible contenant des macropores est présentée.*

Deux solutions sont citées en exemple, traitant le cas d'un sol sans pente avec un fossé d'évacuation.

La première solution est pour un écoulement saturé en régime permanent alors que la seconde traite de l'écoulement variable résultant de pluies d'intensités variables.

Ces exemples ont permis de déterminer que le temps caractéristique nécessaire à la désorption d'un composé chimique donné de la matrice du sol est fonction du taux de transfert de ce composé entre les domaines de macropores.

Lorsque le taux de transfert est nul, le taux de désorption est considérablement ralenti par rapport aux cas où le taux de transfert n'est pas nul.

Le composé chimique s'évacue très rapidement des domaines des macropores lorsque le taux de transfert est nul, alors que l'évacuation est considérablement retardée mais beaucoup plus volumineuse lorsque le taux de transfert du composé chimique n'est pas nul.

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INTRODUCTION

Macropores are generally found in soils of relatively low permeability. In fact, for many soils of this type the presence of macropores is the main avenue through which sufficient water can enter into the soil profile. The importance of macropores in flow and transport processes has been demonstrated by a number of researchers including Stirk (1954), Kissel et al.(1973), Blake et al. (1973), and Ehlers (1975), Bouma and Dekker (1978) and Edwards et al. (1979).

Research on the modeling of water flow in soils containing macropores, or dual-porosity soils, has received much attention as evidenced by the papers given by Hoogmoed and Bouma (1980), Bouma (1981), Beven and Germann (1981), Bronswijk (1988), and Workman and Skaggs (1990). All of these modeling efforts have treated macropore flow as a one-dimensional flow process.

The modeling of multidimensional flow in dual-porosity media appears to have been limited to work on modeling of flow in fractured consolidated rock. An example of this type of application is given by Wang and Narasimhan (1985) where the authors were concerned with the flow of water near nuclear waste repositories.

Current emphasis on increasing the management of agricultural water and chemicals requires field experimentation to examine fundamental processes, and modeling efforts to attempt to extrapolate experimental results. ADAPT (Ward et al., 1988) is an appropriate model to use for both water management as well as chemical management. However, the need to consider the influence of macropore flow on water and chemical movement requires that this model, and other management models like it incorporate macropore flow and transport features. In the development of these water and chemical management algorithms it is useful to have physically-based models to validate the assumptions of the simpler algorithms. This approach was used by R.W. Skaggs and his colleagues (eg. Skaggs and Tang, 1979) in the development of the DRAINMOD (Skaggs, 1986) water management model.

The intent of this paper is to present a simulation model of two-dimensional water flow and solute transport in soils containing macropores. The simulation is based on the numerical solution of the coupled Richards equations for the matrix and the macropores, and the coupled convection-dispersion equations for the matrix and the macropores. An example of drainage from a two-dimensional section of soil is used to illustrate the influence of flow and transport in the macropore domain on chemical mass flux into the drain.

GOVERNING EQUATIONS

The flow domain of interest in the present analysis is represented by a bounded shallow soil profile drained by equally spaced ditch drains. Due to the equal spacing of the drains the analysis can be limited to a region of symmetry as illustrated in Figure 1. The present analysis can also be applied to the case of equally spaced subsurface drains, the only difference being the need to adequately represent the presence of the subsurface drain.

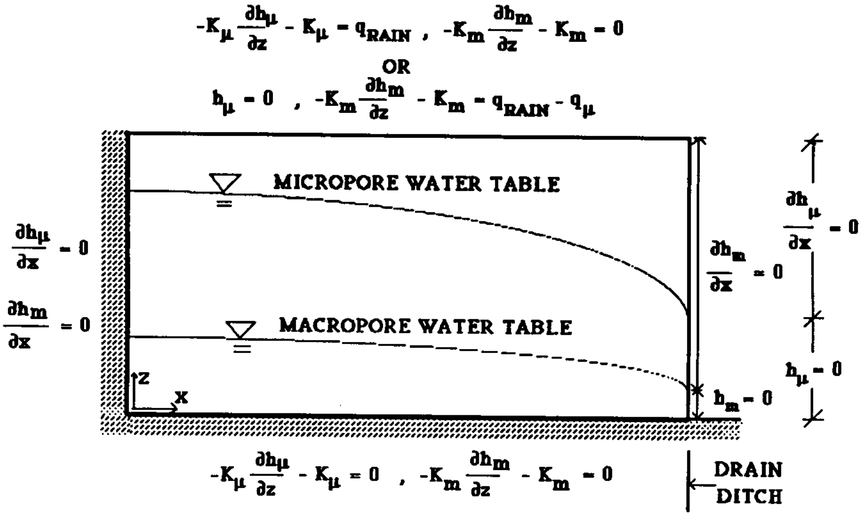

Figure 1. **The flow domain and the boundary conditions for flow and transport to a ditch drain.**

The flow of water in a soil profile containing macropores can be described by a coupled set of mass balance flow equations given by

$$\Phi_\mu \frac{\partial s_\mu}{\partial t} = \nabla . (K_\mu \nabla h_\mu + K_\mu z) + \Gamma_w \tag{1a}$$

$$\Phi_m \frac{\partial s_m}{\partial t} = \nabla . (K_m \nabla h_m + K_m z) - \Gamma w \tag{1b}$$

where the s_μ, h_μ, Φ_μ, and $K\mu$ are respectively the saturation, water pressure, porosity and hydraulic conductivity in the matrix pore domain, the s_m, h_m, Φ_m and K_m are respectively the saturation, water pressure, prtosity and hydraulic conductivity in the macropore domain, and Γw is the rate of transfert from the macropore domain to the matrix domain.

The mass transfer term given in equations (la) and (lb) can be quantified by a number of alternative mathematical expressions, but Gerke and van Genuchten (1992a) have found that one of the most representative forms is given by

$$\Gamma_W = \frac{1.2}{A^2} \overline{K} (h_m - h_\mu)$$

where A is the characteristic half-distance between macropores, and $\overline{K} = \left(0.5 \left(K_\mu(h_\mu) + K_\mu (h_m)\right)\right)$ is the average hydraulic conductivity of the matrix domain at the interface of the matrix and the macropores. In the present analysis the water transfer between domains was only allowed to occur from the macropore domain to the matrix domain. In future work we will consider transfers in both directions.

The boundary conditions for the two pore domains are given by either a specified flux condition or a specified pressure condition as follows:

$$-K_i \frac{\partial h_i}{\partial \eta} - K_i \cos\beta = q_i \qquad i = \mu,m \qquad (2a)$$

$$h_i = H_i \qquad i = \mu,m \qquad (2b)$$

where H_i is the specified pressure in domain i, q_i is the specified flux into domain i, η is the unit vector normal to the flux boundary, and β is the angle between the z-axis and the vector η.

In the present analysis it was assumed that direct rainfall or irrigation does not enter into the macropore domain at the soil surface, but instead only surface runoff generated on the soil matrix will enter the surface connected macropores. The boundary condition for the boundary given by the ditch drain can be represented by a condition of either specified zero flux for the unsaturated flow condition, or the case of specified zero pressure for the case of saturated seepage. These outflow boundary conditions are illustrated in Figure 1 where it is seen that the seepage faces for the two pore domains do not necessarily coincide.

The numerical solution of equations (1) subject to the boundary conditions given in equations (2) was formulated using the finite element method to transform the space derivatives and the finite difference method to discretize the time derivatives. This transformation leads to a set of 2M nonlinear algebraic equations where M is the number of node points.

The modified-Picard method described by Celia et al. (1990) was used to solve these nonlinear equations. The resulting linearized matrix equations were solved for the nodal unknowns using an efficient matrix solver based on the preconditioned conjugate gradient method (van der Horst, 1990; Pini and Gambolati, 1990).

The equations for transport of a dissolved constituent in the dual-porosity system are given by

$$\frac{\partial(\theta_\mu R_\mu C_\mu)}{\partial t} = \nabla . (\theta_\mu D_\mu \nabla C_\mu) - \nabla . (q_\mu C_\mu) + \Gamma_c \qquad (3a)$$

$$\frac{\partial(\theta_m R_m C_m)}{\partial t} = \nabla . (\theta_m D_m \nabla C_m) - \nabla . (q_m C_m) + \Gamma_c \qquad (3b)$$

where the C_μ, R_μ, q_μ and D_μ are respectively the chemical

concentration, retardation coefficient, specific discharge and dispersion coefficient in the matrix domain, the C_m, R_m, q_m and D_m

are respectively the chemical concentration, retardation coefficient, specific discharge and dispersion coefficient in the macropore domain, and Γ_c is the mass transfer rate between the macropore domain and the matrix domain. The flow velocities given in equations (3a) and (3b) are provided by the solutions to the coupled flow equations given by equations (la) and (lb).

The boundary conditions for the transport equations are either those of specified constituent loading rate or specified zero concentration gradient. These boundary conditions are given by

$$-D_i \frac{\partial C_i}{\partial \eta} - q_i C_i = q_i C_{i_{IN}} \qquad i = \mu, m \qquad (4a)$$

$$\frac{\partial C_i}{\partial \eta} = 0 \qquad i = \mu, m \qquad (4b)$$

where C_{iIN} is the solute concentration of the water infiltrating into pore domain i. The transfer of a constituent between the two pore domains was chosen to be quantified by the relationship proposed by Gerke and van Genuchten (1992b) expressed as

$$\Gamma_C = (1 - \chi)\Gamma_W C_m + \chi \Gamma_W C_\mu + \frac{3}{A^2} \overline{D}_{\mu_{diff}} (C_m - C_\mu)$$

where

$$\chi = 0.5\left(1 - \frac{\Gamma_w}{|\Gamma_w|}\right) \qquad \Gamma_W \neq 0$$

$$\overline{D}_{\mu_{diff}} = 0.5\left(D_{\mu_{diff}}(h_\mu) + D_{\mu_{diff}}(h_m)\right)$$

$$D_{\mu_{diff}}(h_\mu) = D_0 \frac{\theta_\mu^{7/3}(h_\mu)}{\theta_{\mu_s}^{2}}, \qquad D_{\mu_{diff}}(h_m) = D_0 \frac{\theta_\mu^{7/3}(h_m)}{\theta_{\mu_s}^{2}}$$

The $\overline{D}_{\mu_{diff}}$ is the effective molecular diffusion coefficient in the water of the matrix domain, D_O is the diffusion coefficient for the chemical in bulk water, and the parameter X determines the direction of chemical transfer by water flow. This functional relationship allows a simple way to quantify the transfer of chemicals between the pore domains.

In addition to quantifying the transfer of chemicals between pore domains a more complete formulation would also quantify the transfer of chemicals from the matrix domain to runoff water flowing on the soil surface. This runoff water would then become infiltration to the macropore domain and would thereby contribute a chemical loading to the macropore system at the soil surface. Models for quantifying the chemical transfer to surface runoff water are represented by Wallach and van Genuchten (1990). The process of transfer of chemicals to surface runoff was not incorporated into the present numerical solution.

The numerical solution of equations (3a) and (3b) subject to the boundary conditions given by equations (4) was formulated using the Galerkin finite element method to transform the space derivatives for both the convective term and the dispersion terms, while a fully-implicit finite difference scheme was used to discretize the resulting set of ordinary differential equations. While the formulation using a standard Galerkin method can lead to numerical oscillations for the case of sharp concentration fronts, the effort involved to incorporate features of upstream weighting with Petrov-Galerkin methods (Huyakorn and Nilkuha, 1979) was not attempted for this paper. A direct banded matrix solver was used to solve the resulting matrix equations. The conjugate gradient method could not be used for these matrices due to their asymmetry.

EXAMPLE SIMULATIONS

To illustrate the use of the numerical solution the flow region illustrated in Figure 1 was used. The region was specified to have a depth of 2.0 meters, a length of 5.0 meters and a width of 1.0 meters. The flow region was discretized into 320 triangular elements and 189 nodes. The van Genuchten (1980) equations with parameters α, n, Ks, $\theta\ s$, $\theta\ r$ were used to represent the matrix and macropore water retention and hydraulic conductivity properties. The parameters used are:

$$\alpha_{\mu} = 0.004\text{m-1},\ \alpha_{m} = 0.4\text{m-1},\ n_{\mu} = 1.8,\ \text{nm} = 5.0,\ \theta_{s\mu} = 0.40,\ \theta_{sm} = 0.03,$$

$$\theta r\mu = \theta_{rm} = 0.0,\ K_{s\mu} = 0.0001\text{m - day}^{-1},\ K_{sm} = 0.4\text{m - day}^{-1}$$

It was of interest to examine the effect of soil heterogeneity on flow and transport, so we examined both homogeneous and heterogeneous soil conditions. The parameter values listed above were used for the homogeneous soil conditions. To incorporate heterogeneous soil property conditions the homogeneous soil properties were used as reference soil properties in a linear scaling procedure. The turning bands method described by Mantoglou and Wilson (1982) was used to generate a two-dimensional field of spatially correlated scaling factors. This scaling factor was used to scale both the water retention function and the hydraulic conductivity using the linear scaling procedure described by Russo (1991).

Parameters to generate the scaling factor (γ) are the mean (μ_{γ}) variance ($\sigma^2\gamma$), and correlation lengths ($l_{\gamma x} l_{\gamma y}$) for the scaling factor. Values for these parameters were selected to be $\mu\gamma$ =0,96, $\sigma^2\gamma = 0\ .\ 063$, $l_{\gamma x} = 0.75$ meters and $l_{\gamma x}$ =0.2 meters. In the present analysis it was assumed that the scaling factor applied to the soil matrix was also applicable to the soil macropore system.

In the first set of simulation results to be presented the flow was specified to be at steady state in both the soil matrix and in the soil macropores. The intention of these simulation results was to illustrate the effect of solute transfer between pore domains on the mass outflow of chemical from the drained soil profile without the complication of transient water flow conditions.

In the second set of simulation results a time series of rainfall input was used to simulate transient water flow and transient chemical transport in the drained soil. The rainfall input was taken from a meteorological record for 1982 at the Hupselse Beek watershed in Holland. The daily rainfall record is illustrated in Figure 2. To convert the daily rainfall to intensities it was assumed that the daily rainfall is uniformly distributed over the day of rainfall. Evapotranspiration was not taken into account in the present analysis although it is expected that evapotranspiration will have a significant impact on flow and transport results. In future work we will account for evapotranspiration in the simulation process.

For both simulation conditions examined in the following analysis, the initial chemical was assumed to be incorporated into the soil matrix (and present in the soil macropores) at the soil surface along the left 2.5 meters of the flow domain. It was assumed that infiltrating rainwater and infiltrating runoff water is free of the chemical. Of interest in future work will be to model the transfer of incorporated chemicals into surface runoff and the infiltration of this solute into the macropore domain.

STEADY STATE WATER FLOW

The soil properties of the matrix and of the macropore domains were considered to be homogeneous for this part of the simulation study. To simulate steady state water flow in the flow domain, the pore domain pressures were set to zero on the soil surface and on the ditch boundary. For this condition the pressures in the two domains at any given point are identical since the resulting pressure distributions do not depend on the pore domain properties. Although the pressure distributions are identical for the two pore domains, the magnitudes of the resulting Darcy fluxes are much larger in the macropore domain.

The initial chemical concentrations in the two domains were set at 1.0 along the left 2.5 meters of the soil surface boundary. It is of interest to examine the effect of the domain transfer of chemicals on the transient outflow of chemicals into the ditch. Three cases were examined. In Case I the transfer of chemicals between the domains was set to zero by specifying the parameter A to be infinity. For Case II and Case III the values for A were 0.10 meters and 0.01 meters respectively. The time dependent mass flux of the chemical from the macropore domain into the ditch drain for the three cases is illustrated in Figure 3, while the mass flux from the matrix domain is illustrated in Figure 4.

The influence of pore domain mass transfer is readily recognized in Figure 3. For Case I the chemical initially present in the macropore domain is transported relatively rapidly out of the flow region. In contrast, as seen in Figure 4 the chemical in the matrix domain is transported so slowly that none of the chemical exits from the domain during the 100 day simulation.

The mass flux out of the macropore domain is delayed in Cases II and III in comparison to that in Case I. This occurs for the following reason. First, in the vicinity of the incorporated chemical, the chemical is transferred from the matrix into the macropore domain due to the higher concentration in the matrix. Down gradient of this location the matrix is initially devoid of chemical so that the chemical transported in the macropore domain is transferred to the matrix domain. This process of up gradient transfer of chemical from the matrix to the macropore domain, and down gradient transfer of chemical from the macropore domain to the matrix delays the migration of the chemical in the macropore domain. Of course, this process also accelerates the leaching of the chemical out of the matrix as indicated by the increased mass of chemical discharging from the ditch boundary in contrast to that found for Case I.

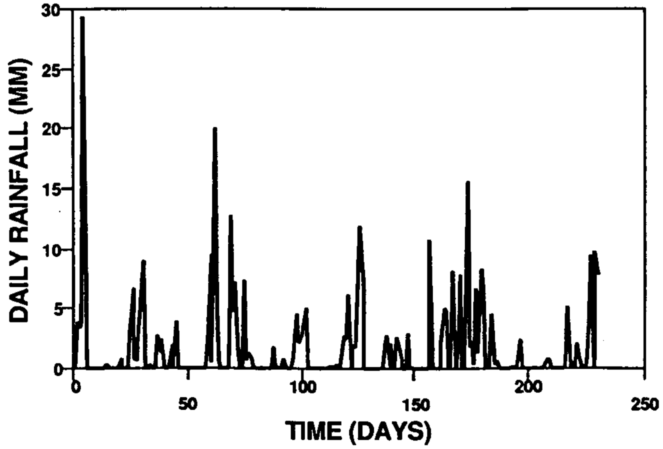

Figure 2. Daily rainfall record used as input for the transient water flow conditions.

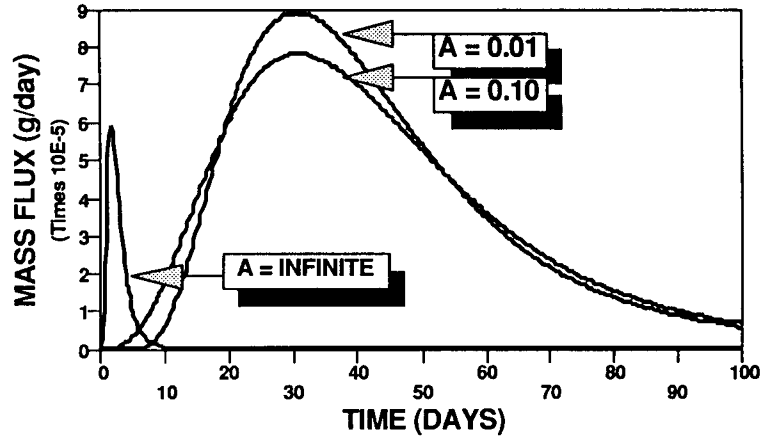

Figure 3. Chemical mass flux from the macropore domain for three pore domain interaction cases for steady state water flow conditions.

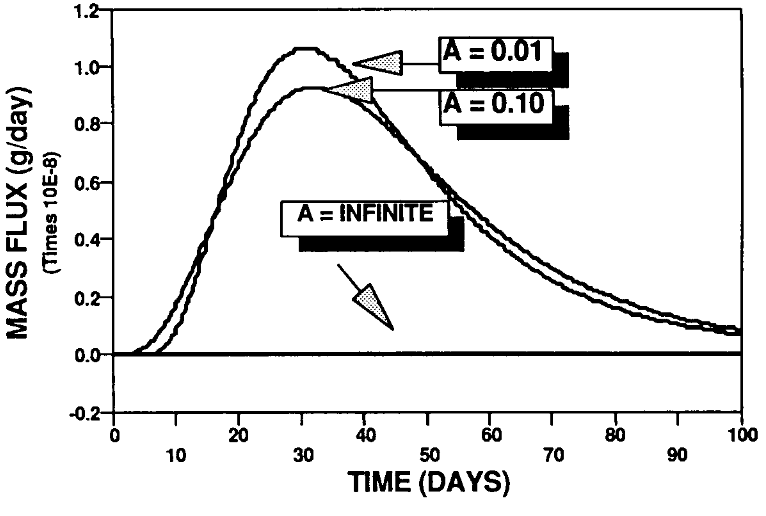

Figure 4. Chemical mass flux from the matrix domain for three pore domain interaction cases for steady state water flow conditions.

Transient Water Flow

The three cases representing three distinct conditions for chemical transfer between pore domains examined in the steady state water flow case above are also considered for the transient water flow simulations. In addition, conditions of homogeneous soil properties and of heterogeneous soil properties were both considered. The initial water pressure distribution in both pore domains was assumed to be hydrostatic. The initial chemical concentration distribution is the same as that used for the steady state water flow case.

Upon examining the resulting discharge hydrographs for the various conditions considered it was found that the transfer of water between the macropore domain and the matrix was not a significant process for all but the first 5 days of the simulation. Due to neglecting evapotranspiration in the water flow simulation the matrix domain never drained significantly and the water pressure remained essentially the same or somewhat greater than the water pressure in the macropore domain. Since we limited the transfer of water between the pore domains only to the case of transfer from the macropore domain to the matrix domain, the water transfer did not occur during the simulation except at the very beginning. Thus the water flow simulations given here do not show sensitivity to the parameter A.

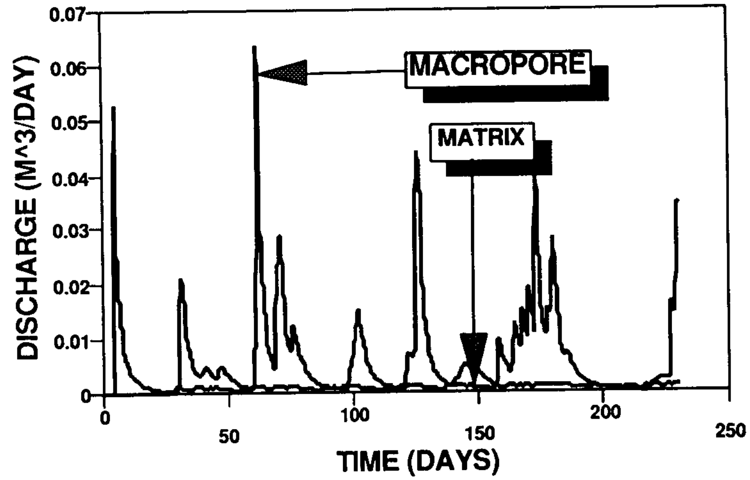

Figure 5. Discharge into the ditch drain from the matrix domain and the macropore domain for the heterogeneous soil condition.

The discharge hydrographs for the heterogeneous flow domain are presented in Figure 5 for both the matrix and the macropore outflows. A comparison of the discharge hydrographs for the condition of homogeneous matrix and macropore properties showed that the discharge hydrographs were relatively insensitive to the degree of heterogeneity considered.here, and thus the hydrographs for the homogeneous porous media condition are not presented. This result does not mean that hydrographs would not be sensitive to more severe degrees of heterogeneity.

The discharge from the matrix domain is seen to show a rapid response to rainfall events, but the magnitude of the response is severely limited by the low hydraulic conductivity of the matrix domain. The reason for the rapid response of the matrix domain is that during the simulation the matrix domain remains near saturation at all times, and therefore any infiltrating rainfall causes a quick response at the drainage ditch.

The macropore domain also produces quick responses to those rainfall events producing runoff from the surface of the matrix domain. This rapid response occurs due to the high conductivity and low water storage capacity of the matrix domain. Although the macropore domain drains rapidly between runoff producing rainfall events, the low retention capacity of the macropore domain facilitates the rapid transmission of water to the ditch outlet.

The chemical mass flux for Cases I, II and III for the macropore domain is illustrated in Figure 6. For Case I the mass flux from the macropore domain is seen to occur rapidly. Early in the simulation all of the chemical initially in the macropore domain is completely discharged from the flow region. The magnitude of the chemical flux from the matrix domain is quite small due to the small amount of chemical mass initially present in the domain.

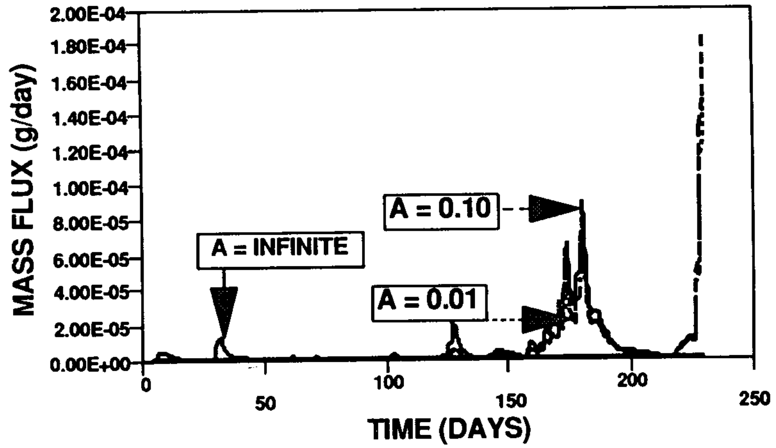

Figure 6. Chemical mass flux from the macropore domain for three pore interaction cases for transient water flow conditions.

The chemical mass flux from the macropore domain for Cases II and III are seen to be delayed relative to the results seen for Case I. reason for this delay was explained in the previous section in reference to Figure 3. The mass flux for Case II is seen to initiate sooner and to be initially larger in magnitude to that for Case III. This result is also consistent with the results seen in Figure 3. Since the simulation was performed for only the 230 day period it is not known whether the chemical mass flux for Case III will surpass that for Case II as observed in Figure 3. However, this is expected to occur.

The chemical mass flux for the matrix domain for Cases I, II and III is presented in Figure 7. For Case I none of the chemical initially present in the matrix domain leaves the flow domain during the 230 day period. An illustration of the chemical mass distribution in the flow domain for Case I at 150 days is illustrated in Figure 8. This contour plot indicates that the chemical mass in the matrix has moved only a small distance during that period of time.

For Cases II and III the chemical mass migration is accelerated due to the interaction with the macropore domain. The chemical mass flux for these two cases are consistent with the results given in Figure 4 for the steady state water flow condition. Outflow of chemical mass is observed to occur at the same time as the outflow of chemical mass from the macropore domain shown in Figure 6. The distribution of chemical in the matrix domain at 150 days for Case III is illustrated in Figure 9.

By comparing Figure 8 and 9 it is seen that the mass transfer with the macropore domain has accelerated the migration rate of the chemical within the matrix domain.

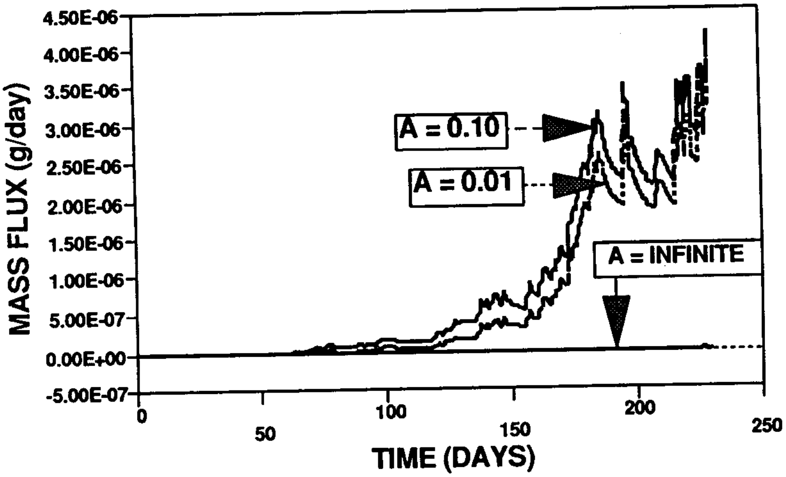

Figure 7. Chemical mass flux from the matrix domain for three pore interaction cases for transient water flow conditions.

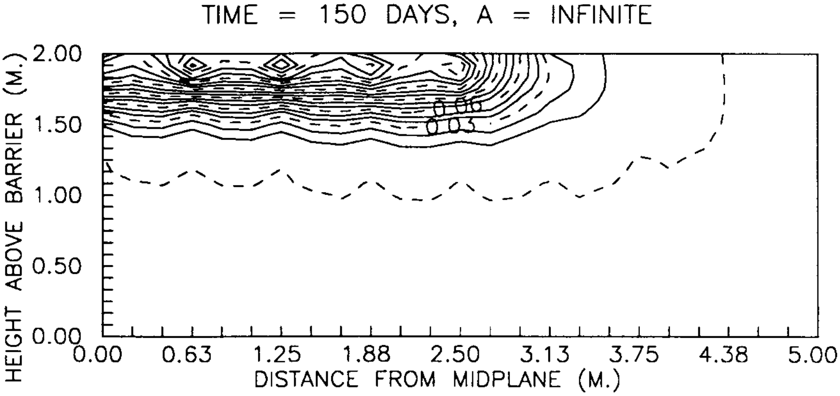

Figure 8. Chemical mass distribution in the matrix domain for Case I at 150 days.

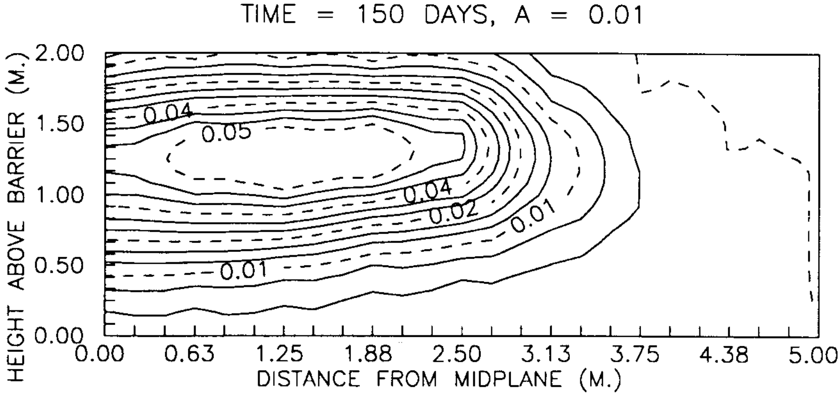

Figure 9. Chemical mass distribution in the matrix domain for Case III at 150 days.

DISCUSSION

The numerical solution procedure presented in the foregoing sections should be useful for examining the processes of water and chemical transport in complicated field conditions. Further treatment of the problem should include the processes of evapotranspiration, unrestricted water transfer between pore domains, chemical adsorption and chemical biodegradation. In addition, the effects of soil heterogeneity need to be evaluated much more completely than they were evaluated here. For instance, it is important to determine the effect of varying macropore densities within the soil profile. Macropore orientation and the effect of this orientation on possible anisotropy in the macropore hydraulic conductivity should also be addressed.

The numerical solution results presented in this paper were derived using a 33 MHz 486 processor microcomputer. The computer program was written in FORTRAN-77 language and the LAHEY 5.01 compiler was used to compile and link the program. Most of the computational effort was involved in solving the water flow equations due to the non linearity of the equations and the boundary conditions.

Improvements in efficiency of the solution might be realized in future work by improvements in the Picard solution procedure, or by use of a Newton-Raphson iterative procedure. Additional improvements can be realized by using operator splitting techniques to solve the transport equations. These techniques split the convective and dispersive parts of the transport equations and solve each part with distinct solution schemes. Usually the convective part of the equation is solved using a characteristic method such as the modified method of characteristics (Chiang et al., 1989). One advantage of operator splitting techniques is that the resulting matrix equations are symmetric and thereby conjugate gradient methods can be used to solve the matrix equations. The use of this iterative matrix solver will be much more significant for the case of when high resolution grids are used to discretize the flow domain. A second advantage of these techniques is that they lead to minimum numerical dispersion even for high Peclet number and high Courant number problems.

The numerical solution procedure presented here is useful as a research tool, but will have limited applicability as a water management model due to the high demand for input data and the computational resource requirements. We propose this model as a method to assist in the activity of learning about the physical and chemical processes of water flow and the fate of agricultural chemicals in drained and irrigated soils.

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SIMULATION OF DRAINAGE WATER QUALITY WITH DRAINMOD

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ABSTRACT. The design and management of drainage systems should consider impacts on drainage water quality and receiving streams, as well as on agricultural productivity. Two simulation models that are being developed to predict these impacts are briefly described. DRAINMOD-N uses hydrologic predictions by DRAINMOD, including daily soil water fluxes, in numerical solutions to the advective-dispersive-reactive (ADR) equation to describe movement and fate of NO_3-N in shallow water table soils. DRAINMOD-CREAMS links DRAINMOD hydrology with submodels in CREAMS to predict effects of drainage treatment and controlled drainage on a Portsmouth sandy loam in eastern North Carolina. Depending on surface depressional storage, agricultural production objectives could be satisfied with drain spacings of 40 m or less. Effects of drainage design and management on NO_3-N losses were substantial. Increasing drain spacing from 20 m to 40 m reduced predicted NO_3-N losses by over 40% for both good and poor surface drainage. Controlled drainage further decreases NO_3-N losses. For example, predicted average annual NO_3-N losses for a 30 m spacing were reduced 20% by controlled drainage. Splitting the application of nitrogen fertilizer, so that 100 kg/ha is applied at planting and 50 kg/ha is applied 37 days later, reduced average predicted NO_3-N losses but by only 3 to 4%. This practice was more effective in years when heavy rainfall occurred directly after planting, however. In contrast to effects on NO_3-N losses, reducing drainage intensity by increasing drain spacing or use of controlled drainage increased predicted losses of sediment and phosphorus (P). These losses were small for relatively flat conditions (0.2% slope), but may be large for even moderate slopes. For example, predicted sediment losses for a 2% slope exceeded 8000 kg/ha for a poorly drained condition (drain spacing of 100 m), but were reduced to 2100 kg/ha for a 20 m spacing. Agricultural production and water quality goals are sometimes in conflict. Our results indicate that simulation modeling can be used to examine the benefits and costs of alternative designs and management strategies, from both production and environmental points-of-view.

RESUME. Simulation de la qualite des eaux de drainage avec DRAINMOD. *La conception et la gestion des systèmes de drainage devraient prendre en compte les impacts sur la qualité des eaux drainées et des cours d'eau récepteurs, aussi bien que sur la productivité agricole. Deux modèles de simulation sont actuellement en cours de développement pour la prédiction de ces impacts; nous les présentons brièvement. Le modèle DRAINMOD-N utilise les prédictions hydrologiques de DRAINMOD, notamment les flux hydriques journaliers dans le sol, pour*

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résoudre numériquement les équations d'advection-dispersion-réaction (ADR) décrivant le mouvement et le devenir de N-NO$_3$ dans les sols présentant une nappe peu profonde. DRAINMOD-CREAMS couple la simulation hydrologique de DRAINMOD avec les sous-modèles de CREAMS pour prédire les effets de l'espacement des drains, des conditions de drainage de surface et du drainage contrôlé des sols sablo-limoneux de Portsmouth dans l'est de la Caroline du Nord (USA). En fonction du volume d'eau stocké dans les dépressions à la surface du sol, les objectifs de production agricole peuvent être atteints avec un espacement de drains de 40 m, ou moins. La conception et la gestion du drainage ont des effets substantiels sur les pertes de N-NO$_3$. En augmentant l'espacement des drains de 20 à 40 m, les pertes prédites de N-NO$_3$ ont été réduites de plus de 40%, que les sols présentent de bonnes ou de mauvaises conditions de drainage de surface. Le drainage contrôlé contribue en plus à réduire les pertes de N-NO$_3$. Il a été par exemple possible de prédire une réduction de 20% des pertes annuelles moyennes de N-NO$_3$ avec le drainage contrôlé. Le fractionnement de la fertilisation azotée, en appliquant 100 kg/ha lors du semis et 50 kg/ha 37 jours plus tard, n'a réduit les pertes moyennes de N-NO$_3$ prédites que de 3 à 4%. Cette pratique était cependant plus efficace les années où de fortes pluies suivaient immédiatement la période de semis. A l'inverse des effets sur les pertes de N-NO$_3$, la réduction de l'intensité du drainage, obtenue soit en augmentant l'espacement des drains, soit en pratiquant le drainage contrôlé, augmentait les pertes prédites de sédiments et de phosphore (P). Ces pertes étaient mineures pour des pentes relativement faibles (0.2%) mais pouvaient devenir importantes pour des pentes même modérées. Les pertes prédites de sédiments, pour une pente de 2% et un sol mal drainé (drains espacés de 100 m), dépassaient par exemple 8000 kg/ha; elles étaient réduites à 2100 kg/ha pour un espacement de 20 m. Les objectifs de production agricole et de protection de la qualité des eaux conduisent parfois à une situation conflictuelle. Nos résultats montrent que les modèles peuvent être utiles pour analyser les coûts et avantages de stratégies alternatives pour la conception et la gestion du drainage, à la fois du point de vue de la production agricole et de la protection de l'environnement.

INTRODUCTION

The traditional objective of agricultural drainage is to increase production and profitability. Past research has focused on productivity by developing methods to design drainage and related water table control systems to improve trafficability, reduce stresses caused by excessive soil water conditions and control salinity. As with most production practices, agricultural drainage affects the amount and quality of water leaving the field and entering receiving surface and ground waters. Research has clearly shown that improved agricultural drainage increases losses of some pollutants and decreases losses of others (e.g. Baker et al. 1975; Bottcher et al. 1981; Gilliam, 1987). Furthermore, drainage water quality and pollutant load are very much dependent on the design and management of drainage and associated water table control systems (Gilliam et al. 1979; Skaggs and Gilliam, 1981). Environmental impacts of agricultural drainage have become an extremely important issue in many areas. Thus, the design of agricultural drainage and related water management systems to satisfy water quality goals or other environmental constraints has become an objective of greater importance than the production objectives in some instances.

Simulation models have been developed to describe the performance of drainage systems, including predicting effects of system design on crop yields and hydrology. These models have been described in previous drainage workshops (e.g. Feddes, 1987; Skaggs, 1987, 1991). Several such models will be demonstrated at this workshop. Numerous models have also been proposed to predict movement and fate of nutrients and pesticides. However, only a few of these models can be applied to quantify the effect of drainage system design and management on losses of agricultural chemicals in shallow water table soils. The purpose of this paper is to describe methods based on DRAINMOD for predicting drainage water quality. Examples are presented to demonstrate application of the model.

MODEL DESCRIPTION

DRAINMOD (Skaggs, 1978, 1991) is a computer simulation model developed to describe the performance of drainage and associated water table control systems in shallow water table soils. The model is based on water balances in the soil profile and at the soil surface. It uses functional methods to describe hydrologic components such as infiltration, subsurface drainage, subirrigation, surface runoff, evapotranspiration (ET), and deep and lateral seepage. Hydrologic predictions of the model have been tested and found to be reliable under a wide range of soil, crop and climatological conditions (e.g. Skaggs, 1982; Fouss et al. 1987; McMahon et al. 1987). Stress-day-index methods are employed to predict effects of excessive and deficient soil water conditions and planting delays on yields (cf. Evans and Skaggs 1993). Mass balance concepts have been recently added to compute average daily soil water fluxes as a function of profile depth (Skaggs et al. 1991). Kandil et al. (1992) used the soil water fluxes predicted by DRAINMOD, in combination with numerical solutions to the advective-dispersive-reactive (ADR) equation to simulate the transport of salt and soil salinity. This version of the model, DRAINMOD-S, was extended to predict effects of salinity on crop yields. Thus, drainage system design may be linked to soil salinity and crop yields in poorly drained, irrigated arid lands. An application of this version of the model will be presented by Kandil et al. (1993) at this workshop.

Two approaches are described herein for predicting effects of drainage system design on movement of pollutants from agricultural fields to receiving waters. The first approach addresses the loss of nitrogen in the nitrate form through subsurface drainage and surface runoff. Nitrate-nitrogen is mobile in the soil water system and is readily lost through subsurface drains. DRAINMOD-N (Breve et al. 1992) is being developed to simulate the nitrogen cycle in shallow water table soils. This model is described and used in this paper to evaluate the effect of drainage system design and operation on nitrate losses. The second approach uses a combination of DRAINMOD and CREAMS (Knisel, 1980; Parsons et al. 1989) to evaluate effects of drainage design on losses of sediment and agricultural chemicals at the field edge. This approach is primarily directed at quantifying the effects of drainage system design on losses of sediment and associated pollutants, such as phosphorus and pesticides, via surface runoff.

DRAINMOD-N

As the name implies, this model is based on the water balance calculations of DRAINMOD. It uses modifications described by Skaggs et al. (1991) to determine average daily soil water fluxes and water contents by breaking the profile into increments and conducting a water balance for each increment. For the saturated zone, vertical fluxes are linearly decreased from Hoodghout's drainage flux at the depth of the water table to zero at the impermeable layer depth. In addition, a water content profile is generated using soil-water characteristic data, based on the assumption that hydrostatic conditions are prevalent in the profile at the end of the day. This approach for computing fluxes and water contents proved to be reliable for shallow water table soils as indicated by comparisons with numerical solutions to the Richards equation for saturated and unsaturated flow (Skaggs et al. 1991; Kandil et al. 1992; Karvonen and Skaggs, 1993). The paper by Karvonen and Skaggs (1993), presented at this workshop, compares solute movement predictions by the two methods, as did Kandil et al. (1992).

The transport of nitrate-nitrogen in the profile is quantified by numerically solving the advective-dispersive-reactive (ADR) equation as described by Breve et al. (1992) and repeated below. The ADR equation may be written as,

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial z}(\theta D \frac{\partial C}{\partial z}) - \frac{\partial(qC)}{\partial z} + \Gamma \qquad (1)$$

where C is the solute concentration [M L^{-3}], D is the coefficient of hydrodynamic dispersion [L^2 T^{-1}], θ is the volumetric water content [L^3 L^{-3}], q is the vertical water flux [L T^{-1}], Γ is a source/sink term used to represent additional processes (plant uptake, transformations, etc.), z is the coordinate direction along the flow path [L], and *t* is the time [T].

Assuming *z* is positive in the downward direction and water flows downward in the soil profile, Eq. (1) can be solved as follows:

$$C_{i_{new}} = \frac{C_{i_{old}} \theta_{i_{old}}}{\theta_{i_{new}}} + \frac{\theta_{i+1_{old}} D_{i+1_{new}} (\frac{C_{i+1_{old}} - C_{i_{old}}}{\Delta z}) - \theta_{i_{old}} D_{i_{new}} (\frac{C_{i_{old}} - C_{i-1_{old}}}{\Delta z})}{\Delta z} \frac{\Delta t}{\theta_{i_{new}}}$$

$$+ \frac{(q_{I_{new}} C_{i-1_{old}} - q_{I+1_{new}} C_{i_{old}}) \Delta t}{\theta_{i_{new}} \Delta z} + \frac{\Gamma \Delta t}{\theta_{i_{new}}} \qquad (2)$$

where C_{old} and C_{new} are the previous time step and resulting solute concentrations [M L^{-3}], respectively, i corresponds to the layer where the concentration is being estimated, I corresponds to the interface between layers i and i-1, and Δz and Δt are space and time discretizations, respectively. An additional term is added for the saturated zone to represent lateral mass flow. Eq. (2) then becomes:

$$C_{i_{new}} = \frac{C_{i_{old}} \theta_{i_{old}}}{\theta_{i_{new}}} + \frac{\theta_{i+1_{old}} D_{i+1_{new}} (\frac{C_{i+1_{old}} - C_{i_{old}}}{\Delta z}) - \theta_{i_{old}} D_{i_{new}} (\frac{C_{i_{old}} - C_{i-1_{old}}}{\Delta z})}{\Delta z} \frac{\Delta t}{\theta_{i_{new}}}$$

$$+ \frac{(q_{I_{new}} C_{i-1_{old}} - q_{I+1_{new}} C_{i_{old}} - q_{li_{new}} C_{i_{old}}) \Delta t}{\theta_{i_{new}} \Delta z} + \frac{\Gamma \Delta t}{\theta_{i_{new}}} \qquad (3)$$

where q_l, the difference between the vertical fluxes entering and leaving the corresponding layer, is the lateral flux going to the drain which is also used to compute solute losses at the drain.

For upward flow the solution is similar to Eq. (3), except that $q_{I,new}C_{i-1,old}$ becomes $q_{I,new}C_{i,old}$, $q_{I+1,new}C_{i,old}$ becomes $q_{I+1,new}C_{i+1,old}$, and the q_l term vanishes, except when water is flowing from the drains as happens in some cases for controlled drainage. In that case, the current model version assumes the water flowing into the domain has a zero solute concentration.

Since DRAINMOD fluxes may be computed at midpoint between the drains or as the average vertical flux in the zone between drains depending on the drainage algorithm used, the predicted solute concentrations correspond to the same location. An average concentration at the drain is approximated by dividing the total lateral mass transport in the saturated zone by the estimated drainage rate.

Because ammonium-nitrogen losses are generally low in poorly drained soils, only nitrate-nitrogen is considered in this version of the model. DRAINMOD-N uses functional relationships to quantify processes other than NO_3-N transport, as follows:

$$\Gamma = \Gamma_{dep} + \Gamma_{fer} + \Gamma_{mnl} - \Gamma_{rnf} - \Gamma_{upt} - \Gamma_{den} \tag{4}$$

where Γ_{dep} stands for rainfall deposition, Γ_{fer} for fertilizer dissolution, Γ_{mnl} for net mineralization, Γ_{rnf} for loss in surface runoff, Γ_{upt} for plant uptake, and Γ_{den} for denitrification.

Fertilizer dissolution is quantified by a zero-order function:

$$\Gamma_{fer} = \frac{A_{fer}}{D_{fer}} \tag{5}$$

where D_{fer} is the depth at which the fertilizer was incorporated [L], and A_{fer} is the amount of fertilizer present in D_{fer} [M L^{-2}]. Fertilizer dissolution is controlled by the soil water content (i.e., fertilizer will dissolve into the soil solution only if the moisture content is greater than a given value). In this version, the threshold moisture content is fixed to a value equivalent to wilting point plus a fraction (0.25) of the difference between saturation and wilting point.

Net mineralization is also represented by a zero-order term:

$$\Gamma_{mnl} = K_{mnl} \rho O_n \tag{6}$$

where K_{mnl} is the net mineralization rate [T^{-1}], ρ is the soil bulk density [M L^{-3}], and O_n is the concentration of organic nitrogen present in the i layer [M M^{-1}]. O_n is estimated using the following expression by Davidson et al. (1978):

$$O_n = O_{nmax} [\exp(-0.025z)] \tag{7}$$

where On_{max} is the maximum organic nitrogen concentration in the top layer.

Plant uptake is estimated using a relationship similar to that employed by Shaffer et al. (1991):

$$\Gamma upt = \frac{Ry \, \%N \, \Delta ft}{Rz} \tag{8}$$

where Ry is a relative yield value [M L^{-2}] obtained from DRAINMOD, %N is the percentage of nitrogen present in the plant/crop, Rz is root length [L], and Δft is a fractional N-uptake demand given by an N-uptake versus growing season curve presented by Shaffer et al. (1991).

Denitrification is approximated by a first-order equation, as follows:

$$r_{den} = K_{den}\,\theta_{iold}\,C_{iold} \qquad (9)$$

where K_{den} is the denitrification rate $[T^{-1}]$.

Rainfall deposition to the surface layer is estimated by assigning a NO_3-N concentration to the infiltrating water. Runoff loss is quantified with the same relationships used in the CREAMS model (Knisel, 1980).

Soil moisture and temperature factors are also used to account for the effect of aerobic or anaerobic conditions and temperature on the different reaction rate coefficients. The functional relationships presented by Johnsson et al. (1987) for denitrification and mineralization are adopted in DRAINMOD-N.

A global mass balance is performed at the end of the simulation: total nitrate-nitrogen amounts present in the soil solution at the beginning and end of the simulation, and cumulative rates for rainfall deposition, fertilizer dissolution, plant uptake, net mineralization, denitrification, and drainage and runoff losses are computed to yield a simulation mass balance error.

Breve et al. (1992) tested the advective component of DRAINMOD-N by comparing predictions with numerical solutions for long-term solute transport. The model is currently being tested with data collected in an intensively instrumented North Carolina field experiment that includes conventional drainage, controlled drainage and subirrigation.

DRAINMOD-CREAMS

CREAMS (Knisel, 1980) was developed by USDA-ARS scientists to simulate edge-of-field loadings of sediment and chemicals, as affected by alternative management practices. These practices include crop rotation, different tillage practices, management of fertilizer and pesticide applications, and conservation practices (strip cropping and contour farming, etc.). CREAMS consists of three submodels to describe field hydrology, erosion and sedimentation, and chemistry (plant nutrients and pesticides). The hydrology submodel was developed for upland soils and does not consider shallow water table conditions. The presence of a water table may have dramatic effects on the amount of water that can be infiltrated. Thus, the system and management may have a strong influence on surface runoff and sediment losses (Skaggs et al. 1982). The combination DRAINMOD-CREAMS model (Parsons et al. 1989) uses DRAINMOD to describe the hydrology and predict the amount of surface runoff. Pass files are created in DRAINMOD to transfer the predicted hydrologic variables to CREAMS where the erosion and chemistry submodels calculate losses of sediment and chemicals.

The erosion and sedimentation submodel of CREAMS describes the processes of soil detachment, transport, and deposition for complex representations of field surface geometry (Foster et al. 1980). Primary particles (sand, silt, and clay) and aggregate size distribution along with modifications of the Universal Soil Loss Equation are used to quantify sediment losses. Overland flow and concentrated flow channels can be described and simulated.

The chemistry submodel considers movement of plant nutrients and pesticides on the surface and through the crop root zone. The nutrient submodel of CREAMS tracks movement of N and P based on a balance in a 1 cm layer at the soil surface (Frere et al. 1980). The leached soluble phosphate compounds are assumed to stay in equilibrium with the soil. Soluble phosphorous in the surface runoff is based on the extraction coefficient for movement in runoff.

Soluble forms of the nutrients can be leached with infiltration of rainfall. Soluble nitrogen compounds are assumed to be nitrates or converted to nitrates for the addition to the root zone pool. The amount of N available for runoff is based on change in concentration in the surface layer taking into account rainfall N, the downward movement and the extraction coefficients for downward movement. A budget for nitrogen and water in the root zone is maintained. Balances are maintained for the mineralization of soil organic N, plant uptake, denitrification and leaching.

Wright et al. (1992) modified the denitrification component for application in the linked model. By assuming that chemicals leached from the bottom of the root zone are conservative, losses via subsurface drainage can be predicted. However, this model does not treat transport and transformations of solutes below the root zone. Because CREAMS was developed to predict effects of management practices on losses of sediment and chemicals in surface runoffs, the linked model is recommended; for that purpose. Wright et al. (1992) tested the linked model by comparing predicted sediment and nitrogen losses to values measured in experiments in Louisiana. They found acceptable agreement that was much improved over predictions using CREAMS alone. This model is being further tested in the experimental studies cited above for DRAINMOD-N.

APPLICATIONS

The models discussed above were applied to evaluate effects of drainage and water table control on losses of sediment and fertilizer nutrients from a corn field in eastern North Carolina. The soil is Portsmouth sandy loam, a fine loamy over sandy or sandy-skeletal mixed Thermic, Typic Umbraquult. Portsmouth is very poorly drained in its natural state with slopes ranging from 0 to 2 percent. Simulations were conducted to determine the effects of subsurface and surface drainage intensities, controlled drainage and timing of fertilizer applications on losses of sediment, nitrate-nitrogen and phosphorus at the field edge. Yields were also predicted and the effect of land slope is considered.

Model Inputs

Inputs for DRAINMOD-N and the DRAINMOD-CREAMS models are given in Table 1. Simulations were conducted for continuous corn over a 20-year period (1971-1990) of climatological record at Plymouth, NC. The field was assumed to be 200 m long with a drainage ditch on either end which receives surface runoff and serves as an outlet for subsurface drains. The surface is on a slight grade (0.2%) with the highest point midway between the ditches so that the slope length, and effective field length is 100 m. One set of simulations was conducted for a slope of 2.0% to show the effect of drainage on sediment and P losses for moderately sloped, as well as for nearly flat fields. The drainage system consisted of parallel 10-cm diameter corrugated plastic drains buried at a depth of 1.0 m. Drain spacings ranging from 20 to 100 m were considered. The surface drainage intensity is characterized by the depth of depressional storage' s. Two values are considered: s=0.5 cm (good surface drainage) and s=2.5 cm (poor surface drainage).

1.	**Soil Properties**:	**Portsmouth Sandy Loam**
	θ_{sat} (cm^3 cm^{-3})	0.37
	θ_{wp} (cm^3 cm^{-3})	0.17
	Bulk Density (g cm^{-3})	1.1
	Organic Matter (% wt)	7.0
	Organic-N in top soil (μg g^{-1})	3300
	Lateral Sat. Hyd. Cond. (m d^{-1})	3.60 (0-30 cm) 0.48 (30-100 cm) 1.92 (100-215 cm)
2.	**Drainage System Parameters**:	
	Drain Depth (m)	1.0
	Drain Spacing (m)	20, 30, 40, 50, and 100
	Depth to Impermeable Layer (m)	2.15
	Effective Drain Radius (cm)	1.5
	Surface Storage (cm)	0.5 and 2.5
3.	**Controlled Drainage Parameters**:	
	Weir Depth Set to	40 cm - Nov 1 to Mar 15
	Weir Depth Set to	50 cm - May 15 to Aug 15
4.	**Corn Production Parameters**:	
	Desired Planting Date	April 15
	Length of Growing Season (d)	130
	Max. Effective Root Depth (cm)	30
	P-Fertilizer Input (kg ha^{-1})	78
	N-Fertilizer Input (kg ha^{-1})	150 and 100+50 (Split)
	Date Fertilizer Application	April 15 and May 22
	Depth Fertilizer Incorporated (cm)	10
5.	**Nitrogen Movement and Fate Parameters (DRAINMOD-N)**:	
	Dispersivity (cm)	5.0
	K_{mnl} (d^{-1})	4.0E-05
	K_{den} (d^{-1})	0.3
	Potential Yield (kg ha^{-1})	10000
	NO_3-N Content of Plant (%)	1.55
	NO_3-N Concentration of Rain (mg L^{-1})	0.8
6.	**Erosion Parameters (DRAINMOD-CREAMS)**:	
	Field Slope (%)	0.2 and 2.0
	Slope Length (m)	100
	Soil Erodibility Factor (K)	0.24
	Cover Management Factor (C)	0.14-0.72
	Manning's Coefficient (n)	0.01-0.04

Table 1. Summary of inputs for DRAINMOD-N and DRAINMOD-CREAMS Results

Effects of drainage spacing and surface drainage intensity on the hydrologic components are shown in Table 2. Increasing the drain spacing reduces subsurface drainage while increasing ET and surface runoff. Improving surface drainage by filling potholes and grading the surface to reduce depressional storage increases surface runoff and decreases subsurface drainage. Controlled drainage reduces subsurface drainage intensity, thus reducing drainage outflows and increasing surface runoff and ET compared to conventional drainage. Clearly design of the drainage system and its management affects both the route and rate that excess water is removed from the field. It follows that losses of agricultural chemicals will also be affected.

Drain	Good Surface Drainage, S=0.5 cm				Poor Surface Drainage, S=2.5 cm			
Spacing (m)	ET (cm)	Drainage (cm)	Runoff (cm)	Rel.Yield (%)	ET (cm)	Drainage (cm)	Runoff (cm)	Rel.Yield (%)
Conventional Drainage								
20	71.4	57.8	3.2	82.2	71.5	59.7	1.3	81.6
30	73.0	55.2	4.2	82.4	73.1	57.7	1.7	81.2
40	74.9	51.9	5.7	81.3	75.1	55.1	2.2	78.7
50	76.8	48.3	7.3	77.7	77.2	52.4	2.8	73.0
100	83.0	34.3	15.2	62.7	84.4	42.3	5.7	42.5
Controlled Drainage								
20	72.8	55.7	3.9	83.5	72.9	58.0	1.6	82.2
30	74.4	53.0	5.1	81.3	74.5	55.9	2.0	77.8
40	76.2	49.6	6.6	78.6	76.4	53.4	2.6	72.0
50	78.0	46.0	8.4	74.3	78.4	50.8	3.2	64.6
100	83.5	32.4	16.6	58.5	85.0	40.8	6.6	36.8.

Table 2. Average annual values of hydrologic components predicted by DRAINMOD for a Portsmouth sandy loam soil at Plymouth, NC. Values are averages predicted for the 20-yr period 1971-1990 in which the average annual rainfall = 132.1 cm.

Predicted components of the nitrate-nitrogen budget, water table depth, and rainfall are plotted versus time for a relatively wet year (rainfall = 170 cm) in Figure 1. Heavy rainfall during days 60 to 85 and 260 to 275 resulted in shallow water table depths which increased denitrification and drainage losses. Both denitrification and drainage losses during this wet year were greater than in other years. For example, denitrification in 1986, a relatively dry year (rainfall = 102 cm) was 100 kg/ha compared to 120 kg/ha for 1989 (Fig. 1). Total predicted drainage and runoff losses were 15 kg/ha in 1986 compared to 44 kg/ha for the wet year. A summary of the predicted nitrate-nitrogen budget is given in Table 3 for the range of drain spacings considered. Wider drain spacings and the use of controls on the drainage outlets reduce average water table depths and increase water contents in the profile. This causes net mineralization to decrease and denitrification to increase with wider spacings and the application of controlled drainage.

Drain Spacing	Fertilizer Input	Net Mineralization	Rainfall Deposition	Plant Uptake	Denitrification	Losses Drainage	Runoff
(m)			(kg/ha/yr)				
Conventional Drainage							
20	150.0	95.0	9.3	114.8	100.9	31.4	0.3
30	150.0	93.3	9.2	115.6	105.1	24.2	0.3
40	150.0	92.7	9.1	116.0	109.9	17.8	0.5
50	150.0	92.3	8.9	112.1	115.5	13.2	0.7
100	150.0	90.6	8.2	90.0	136.0	6.0	1.8
Controlled Drainage							
20	150.0	94.7	9.2	116.4	106.2	24.5	0.3
30	150.0	94.2	9.1	116.0	110.5	19.2	0.4
40	150.0	93.7	9.0	113.3	114.9	14.8	0.6
50	150.0	93.0	8.8	108.6	119.6	11.5	0.8
100	150.0	90.8	8.1	84.7	140.1	5.6	2.1.

Table 3. Predicted annual nitrate-nitrogen budget for corn production on a Portsmouth sandy loam with good surface drainage (S=0.5 cm) at Plymouth, NC. Values are averages for a 20-yr period (1971-1990).

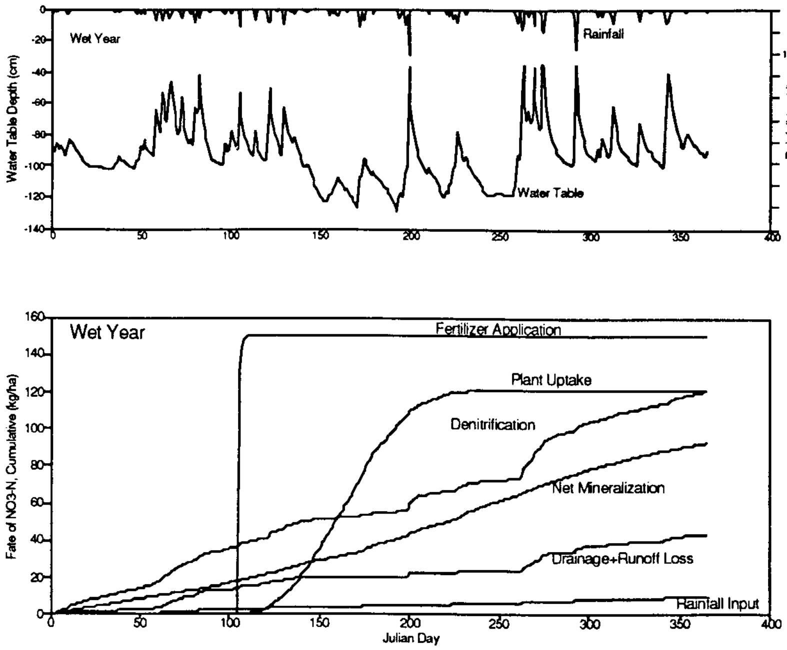

Figure 1. Rainfall, water table, and sources and sinks of nitrate as functions of tume for a wet year (1989, rainfall = 176.0 cm). Results predicted by DRAINMOD-N for Portsmouth sandy loam wih a 30 m drain spacing with good surface drainage.

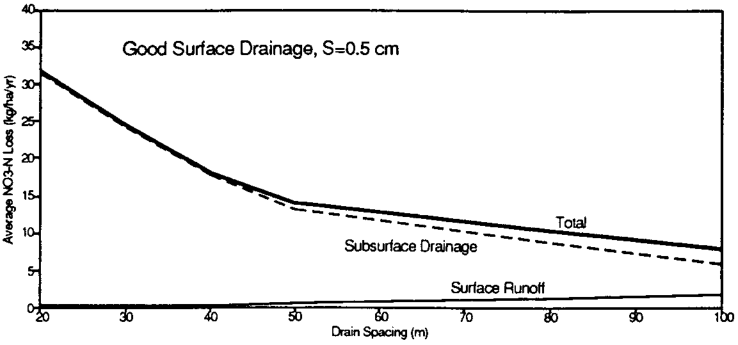

Figure 2. Average annual-nitrogen losses as affected by drain spacing for Portsmouth sandy loam with good surface drainage (S = 0.5 cm). Total loss is the sum of losses via subsurface drainage and surface runoff.

Effects of drainage treatment on average annual NO_3-N, phosphorus (P) and sediment losses are summarized in Table 4. Nitrate-nitrogen losses were predicted with DRAINMOD-N while sediment and P losses were determined with DRAINMOD-CREAMS. Nitrate-nitrogen losses are very dependent on drainage intensity. Average annual surface, subsurface, and total NO_3-N losses are plotted versus drain spacing in Figure 2. Predicted surface runoff losses increase with drain spacing but are small for all cases, compared to subsurface losses. Subsurface NO_3-N losses and total losses decrease rapidly with increased drain spacing. Nitrate-nitrogen losses to receiving waters can be reduced by improving surface drainage. However the effect is small compared to that obtained by reducing subsurface drainage intensity. For example filling depressions to change surface storage from 2.5 cm to 0.5 cm would reduce average annual losses 5.4% (from 25.9 to 24.5 kg/ha) for a 30 m drain spacing. However, increasing the drain spacing from 30 to 40 m would reduce NO_3-N losses by 26% (from 24.5 to 18.3 kg/ha). Controlled drainage can be used to substantially reduce NO_3-N losses according to predictions given in Table 4. For example, controlled drainage reduced predicted losses for the 20 m spacing by 22% (from 31.7 to 24.8 kg/ha) for fields with good surface drainage. Effects were about the same for poor surface drainage where controlled drainage reduced losses by 20% for the 20 m spacing.

Drain Spacing	Good Surface Drainage, S=0.5 cm					Poor Surface Drainage, S=2.5 cm				
	NO$_3$-N Loss*			Sed.**	P**	NO$_3$-N Loss*			Sed.**	P**
	Total	Drainage	Runoff	Loss	Loss	Total	Drainage	Runoff	Loss	Loss
(m)						(kg/ha/yr)				
Conventional Drainage										
20	31.7	31.4	0.3	80	0.2	33.0	32.9	0.1	30	0.1
30	24.5	24.2	0.3	110	0.3	25.9	25.8	0.1	40	0.1
40	18.3	17.8	0.5	160	0.4	19.5	19.3	0.2	50	0.2
50	13.9	13.2	0.7	210	0.6	14.8	14.6	0.2	60	0.2
100	7.8	6.0	1.8	470	1.3	8.2	7.6	0.5	150	0.4
Controlled Drainage										
20	24.8	24.5	0.3	100	0.3	26.4	26.3	0.1	40	0.1
30	19.6	19.2	0.4	130	0.4	21.3	21.0	0.2	40	0.1
40	15.4	14.8	0.6	180	0.5	16.8	16.6	0.2	50	0.2
50	12.3	11.5	0.8	230	0.7	13.5	13.2	0.3	70	0.2
100	7.7	5.6	2.1	490	1.4	7.8	7.2	0.6	170	0.5

* Simulated with DRAINMOD-N

** Simulated with DRAINMOD-CREAMS.

Table 4. Average annual losses of sediment and fertilizer nutrients as affected by drainage treatment. Results were predicted for production of continuous corn on a Portsmouth sandy loam at Plymouth, NC.

A method often proposed for reducing nitrate losses is to split the application of nitrogen fertilizer so that part of it is applied at planting with the remainder added later in the growing season. The hypothesis is that this strategy will diminish losses due to heavy rainfall events directly after planting when fertilizer is normally applied. Results in Table 4 were simulated for a single application of nitrogen fertilizer (150 kg/ha) as shown in Figure 1. Predicted annual NO$_3$-N losses for a split application, 100 kg/ha at planting with an additional 50 kg/ha 37 days later, are given in Table 5. Comparison with results in Table 4 shows that NO$_3$-N losses may be reduced by splitting the application, but the effect is relatively small. For example, splitting the application for a 20 m spacing with good surface drainage reduced the average annual losses about 3.5% from 31.7 to 30.6 kg/ha. The effect was greater in years with heavy rainfall directly after planting, but based on long-term averages, the predicted effect is small. The effect of splitting the fertilizer application could be substantial for other locations with different rainfall characteristics however.

Drain Spacing	Good Surface Drainage, S=0.5cm			Poor Surface Drainage, S=2.5cm		
	NO_3-N Loss			NO_3-N Loss		
	Total	Drainage	Runoff	Total	Drainage	Runoff
(m)	(kg/ha/yr)					
Conventional Drainage						
20	30.6	30.3	0.3	31.6	31.5	0.1
30	23.6	23.3	0.3	24.8	24.7	0.1
40	17.7	17.2	0.5	18.8	18.6	0.2
50	13.7	13.0	0.7	14.6	14.4	0.2
100	7.7	5.9	1.8	8.1	7.6	0.5
Controlled Drainage						
20	24.1	23.8	0.3	25.5	25.4	0.1
30	19.1	18.7	0.4	20.6	20.4	0.2
40	15.1	14.5	0.6	16.4	16.2	0.2
50	12.2	11.4	0.8	13.3	13.0	0.3
100	7.6	5.5	2.1	7.8	7.2	0.6.

Table 5. Average annual nitrate-nitrogen losses as affected by drainage treatment. Results were predicted by DRAINMOD-N for a split application of nitrogen fertilizer.

The same factors that reduce NO_3-N losses tend to increase losses of sediment, P and other contaminants that are primarily transported by surface runoff. Predicted losses of sediment and P for this flat (0.2% slope) Portsmouth soil are small. However, increasing the drain spacing from 20 to 40 m increased predicted losses of both P and sediment by a factor of 2 for fields with good surface drainage (Table 4). Application of controlled drainage also increased predicted losses of sediment and P.

Effects of drainage intensity on surface losses are more critical on lands with greater slope. In order to demonstrate these effects, a set of simulations was conducted for a slope of 2%, which is the upper end of the range for the Portsmouth soil. Results predicted by the DRAINMOD-CREAMS model are summarized in Table 6. Predicted sediment and P losses at the field edge were substantially higher for the increased field slope. For example annual sediment losses were 2800 kg/ha for a 30 m spacing with good surface drainage compared to only 110 kg/ha for the same drainage treatment with 0.2% slope. Results in Table 6 demonstrate the effectiveness of subsurface drainage in controlling erosion and the movement to surface waters of sediment and other contaminants. Increasing the intensity of subsurface drainage (by placing the drains closer together and/or deeper) results in lower water tables prior to storm events. This reduces surface runoff (Table 2) which, in turn, reduces erosion and the losses of sediment and chemicals carried by the runoff water. Although subsurface drainage is not normally considered to be an erosion control practice, it is recommended for that purpose in some locations; results in Table 6 show that it would be very effective for poorly drained soils. For example installing additional drains to change the spacing from 100 m to 20 m for a 2% field slope would reduce average annual sediment losses by a factor of 4 from 8600 kg/ha to 2100 kg/ha. This effect is consistent with results of field research showing that subsurface drainage can substantially reduce losses of sediment and associated contaminants (Bengtson et al. 1988; Istok and Kling, 1983; Bottcher et al. 1981).

Drain Spacing		Good Surface Drainage, S=0.5cm				Poor Surface Drainage, S=2.5cm			
		Sediment		Phosphorus		Sediment		Phosphorus	
	Slope:	0.2	2.0	0.2	2.0	0.2	2.0	0.2	2.0
(m)	(%)	(kg/ha/yr)							
20		80	2100	0.2	1.6	30	710	0.1	0.6
30		110	2800	0.3	2.2	40	960	0.1	0.8
40		160	3700	0.4	2.9	50	1300	0.2	1.0
50		210	4600	0.6	3.6	60	1500	0.2	1.2
100		470	8600	1.3	7.0	150	3600	0.4	2.8.

Table 6. Effect of drain spacing and slope on predicted annual losses of sediment and P from a Portsmouth sandy loam near Plymouth, NC.

Effects of drainage intensity on yields and NO_3-N losses are shown in Figure 3. These results demonstrate both the benefits of simulation modeling and the complexity of designing drainage systems to simultaneously satisfy production and environmental objectives. Nearly optimum yields of about 82% of the potential yield can be obtained with drain spacings less than 40 m for good surface drainage (Table 2). The potential yield is the yield that would be obtained if soil water stresses are eliminated. Stresses due to excessive soil water conditions can be eliminated by increasing drainage intensity. However, drought stresses limit the long-term average to about 82%. The drain spacing that would provide maximum profit to the farmer can be determined by an economic analysis that considers both the costs and benefits of alternative designs. Because the cost of the system decreases with increased spacing, maximum profits would be obtained for a spacing of about 40 m. However, soil properties for a given soil series vary widely from field to field. In the absence of detailed soil investigations and design for a particular site, drain spacing recommendations tend to be conservative or on the "safe" side. Thus a 20 to 30 m spacing would be typical for a Portsmouth soil. This system would be more expensive than necessary, but would satisfy production objectives.

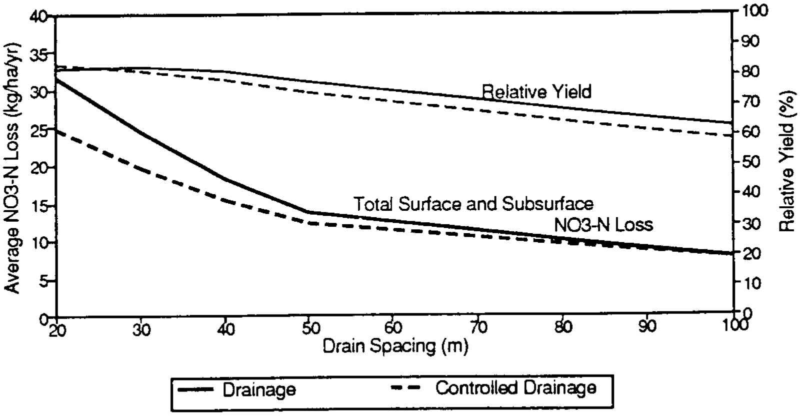

Figure 3. Predicted average annual relative yields and losses of NO_3-N as affected by drain spacing and controlled drainage for a Portsmouth sandy loam with good surface drainage.

If the objective is to satisfy production requirements while minimizing NO_3-N losses to receiving streams, there is a strong incentive for reducing drainage intensity as much as possible. Increasing the drain spacing from 20 to 40 m would reduce yields by only 1% but reduce NO_3-N losses from 31.7 to 18.3 kg/ha/yr (42% reduction). By using controlled drainage with the 40 m spacing, NO_3-N losses could be further reduced by 16% to 15.4 kg/ha/yr, but yields would also be reduced by about 3% (Table 2).

Nitrate-nitrogen losses could be further reduced by the use of even wider drain spacings as shown in Figure 3 and Table 4. The "cost" would be reduced yield and profit to the farmer. However, this cost may be far less than the alternative environmental costs caused by NO_3-N in the drainage water. From a societal perspective, it might be less expensive to pay higher prices for grain (or subsidize the farmer for lost profits), compared to treating the water to remove excessive NO_3-N or the alternative environmental costs. However, reducing drainage intensity may involve costs in addition to decreased yields and profits. Increasing the drain spacing from 20 m to 40 m would increase P and sediment losses by a factor of 2. Use of controlled drainage would further increase those losses. The magnitude of P and sediment losses is small for the nearly flat soils considered herein. But the losses can be large as shown in Table 6. The relative importance of controlling NO_3-N, P and sediment entry to the environment depends on the water quality status of the receiving streams. In some cases it may be more important to control P, in others NO_3-N. In any case simulation models can be used to evaluate the alternatives. The models used herein are still being tested and developed. While the direction of changes in water quality predicted for different drainage intensities are consistent with field observations, the magnitudes of those changes are obviously subject to the validity of the models.

SUMMARY

Two models, DRAINMOD-N and DRAINMOD-CREAMS, for predicting losses of sediment and agricultural chemicals from artificially drained soils were briefly described. The models are being developed to predict the effects of drainage system design and management on nonpoint source pollution and drainage water quality. The models were demonstrated by analyzing effects of drain spacing, surface drainage treatment and controlled drainage on crop yield and losses of sediment and fertilizer nutrients. Analysis of the results indicates that it may be possible to substantially reduce NO_3-N losses without reducing profitability by reducing drainage intensity to the minimum needed for producing the crop. However, practices that reduce NO_3-N losses tend to increase field losses of sediment and P, so design and management for a given site should consider the water quality status of the receiving stream.

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COMPARISON OF DIFFERENT METHODS FOR COMPUTING DRAINAGE WATER QUANTITY AND QUALITY

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ABSTRACT. Computer simulation models have been developed for soils with shallow water tables which may include drainage and water table control systems. The purpose of this paper is to provide comparisons between predictions by two different models: the numerical solution of the Richards equation and DRAINMOD. Predictions by both models were compared for conditions in Finland on four different soils. The computed results by the two models were generally in good agreement for both water balance components and solute transport components. It was concluded that DRAINMOD provides reliable results for a wide range of soils and boundary conditions.

INTRODUCTION

Simulation models that are based on solutions to the governing flow equations predict the flux at all points in the profile. The most exact approach is to solve the two-dimensional Richards equation for saturated and unsaturated flow. These solutions have been used to study mostly short-term events and to test approximate methods (e.g. Fipps et al. 1986). In a few cases solutions have been obtained to simulate conditions for several months (e.g. Zaradny et al. 1986a,b). However, this approach is difficult to use and computational requirements limit its application.

Several simulation models have been based on numerical solutions to the Richards equation for one-dimensional (vertical) flow (Feddes et al. 1978; Karvonen, 1988; Workman, 1990). Lateral water movement in the saturated zone is considered by using drainage theory to define the relationship between flux and water table elevation. This approach requires far less computer time and is easier to apply than the two-dimensional solutions. Vertical fluxes are predicted at all depths in the profile, so methods to predict solute movement can be incorporated.

DRAINMOD (Skaggs, 1978) is a computer simulation model developed for soils with shallow water tables which may include drainage and water table control systems. The model is based on a water balance in the profile and uses approximate methods to quantify hydrologic components such as infiltration, subsurface drainage, subirrigation, surface runoff and lateral seepage and evapotranspiration. It has been tested and found to be reliable for a wide range of soil, crop and climatological conditions (e.g. Skaggs et al., 1981; Skaggs, 1982; Gayle et al., 1985; Fouss et al. 1987; Rogers, 1985; McMahon et al. 1987; and Susanto et al., 1987). The advantages of DRAINMOD are that it is numerically stable, easier to use and computer execution times are much faster than methods based on numerical solutions to the governing flow equations.

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The computational requirements of the numerical solution of the Richards equation are at least an order of magnitude greater than DRAINMOD.

Methods have been developed to estimate vertical fluxes in DRAINMOD (Skaggs et al. 1991) and Kandil et al. (1992) have used the method in modeling long-term solute transport in drained unsaturated zones. The purpose of this paper is to compare flux predictions and estimated water balance terms of DRAINMOD with those obtained from numerical solutions to the Richards equation. Moreover, the same solute transport subroutine was included in both models to compare the influence of calculated fluxes on redistribution of a given initial concentration profile and on the drainage water quality.

COMPUTATION OF FLUXES AND SOLUTE TRANSPORT

Determining vertical fluxes in DRAINMOD

A simple soil water content distribution is assumed in DRAINMOD. The model calculates the water table depth on hour-by-hour, day-by-day basis by assuming that the soil profile is drained to equilibrium above the water table, i.e. $h = -x$, where h is the soil water pressure head and x is the distance above the water table. The average flux over a time step at any distance below the surface is determined by breaking the profile into depth increments, dz, and calculating the volume of water dV removed or added to each increment. Details of the computational procedure have been given by Skaggs et al. (1991).

Determining vertical fluxes from the Richards equation

Vertical fluxes can be obtained directly from simulation models based on solutions to Richards equation. The description of the numerical solution used in this study has been given by Karvonen (1988).

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial h}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] - \frac{\partial K(h)}{\partial z} - S(h) \qquad (1)$$

where h is the soil water pressure head, t is time, z is vertical position (positive downward from the soil surface), C(h) is the soil water capacity ($C(h) = dh/d\theta$), θ is the volumetric water content, K(h) is the unsaturated hydraulic conductivity function and S(h) is a sink term representing the rate of water uptake by plant roots. In this study, the equation is applied to a vertical profile located midway between parallel drains.

The lower boundary condition is specified as a flux to subsurface drains determined from Hooghoudt's equation (van Schilfgaarde 1974) and the calculated water table elevation midway between the drains. In this study the same subroutine was used both in Richards equation and in DRAINMOD.

Computation of solute transport

In general, the common transport-adsorption models proposed in the literature are partial differential equations. The differential equation used to describe one-dimensional convective dispersion of a solute in uniform porous media is:

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial z}[D\frac{\partial C}{\partial z}]-\frac{\partial(vC)}{\partial z}-\frac{\sigma}{\theta}\frac{\partial S}{\partial t}\pm\Omega i \qquad (2)$$

where C is the solution concentration, z is vertical coordinate, D is dispersion coefficient, v is the seepage velocity ($v = q/\theta$), q is the Darcy flux through the soil, θ is the volumetric water content, S is the adsorbed phase concentration , σ is the bulk density of the porous medium and Ω_i describes transformations influencing the solute cycle.

The primary goal of this paper is to compare the influence of the computed fluxes on solute transport and therefore only the convection part of Eq. (2) was taken into account. The numerical solution of Eq. (2) was used to calculate the vertical distribution of the concentration profile. In the horizontal direction water was assumed to be taken from all nodes below the water table and concentration of drainage water was calculated as a weighted average. The same procedure was applied for both models.

PROCEDURES

Simulations with both DRAINMOD and the Richards equation model were conducted for four soils. A parallel drainage system was assumed for each soil and simulations were conducted for two years of climatological data from Jokioinen Agricultural Research Station in Finland.

Input data

The four generic soils considered were homogenous profiles with the following textures: 1. sandy, 2. fine sand, 3. loess loam and 4. clay. The soil water characteristics were calculated by the methods of van Genuchten (1980). The unsaturated hydraulic conductivity was calculated from the soil water characteristic using the Millington and Quirk (1962) procedures as applied in the SOILPREP program of DRAINMOD. Properties for each soil are given in Table 1.

	CLAY		SAND FINE		SAND		LOESS LOAM	
h	θ	K	θ	K	θ	K	θ	K
0	0.453	0.10000	0.46	4.00000	0.36	2.00000	0.46	0.60000
-10	0.445	0.04227	0.44	2.13521	0.33	0.19425	0.43	0.09018
-20	0.436	0.01986	0.40	1.02076	0.29	0.05607	0.41	0.03402
-30	0.428	0.01189	0.36	0.44991	0.27	0.02278	0.39	0.01619
-40	0.421	0.00774	0.32	0.20629	0.25	0.01116	0.38	0.00911
-50	0.414	0.00543	0.29	0.09876	0.24	0.00594	0.37	0.00575
-60	0.408	0.00407	0.26	0.05087	0.22	0.00355	0.36	0.00384
-80	0.397	0.00235	0.22	0.01616	0.21	0.00158	0.34	0.00201
-100	0.387	0.00148	0.19	0.00628	0.19	0.00085	0.33	0.00117
-150	0.370	0.00062	0.15	0.00102	0.17	0.00025	0.30	0.00042
-200	0.357	0.00031	0.13	0.00029	0.15	0.00010	0.29	0.00021
-250	0.346	0.00018	0.11	0.00009	0.14	0.00005	0.28	0.00011
-300	0.339	0.00012	0.10	0.00004	0.13	0.00003	0.27	0.00007
-350	0.332	0.00008	0.09	0.00003	0.12	0.00002	0.26	0.00005

Table 1. Soil Water Characteristic θ(h) and hydraulic conductivity K(h) (cm h^{-1}) for the soils analyzed in this study.

Depth to an impermeable layer was taken as 1.4 m for all four soils. The relationships between water table depth, drainage volume and maximum steady upward flux from the water table were computed from θ(h) relationships for each soil using the SOILPREP program, DRAINMOD Version 4.0.

The assumed distance between parallel drains varied with the soil as follows: 20 m for sandy soil and fine sand, 15 m for loess loam and 10 m for clay soil. Drain depth was taken as 1.0 m making the distance from the drains to the impermeable layer 0.4 m for all soils. The drains were assumed to be 100 mm in diameter corrugated plastic with an effective radius (to account for convergence to the drain openings) of 15 mm (Dierickx 1980).

In the calculation of the solute transport the following initial concentration profile was given for both models: 15 mg l^{-1} between 0-30 cm and 5 mg l^{-1} below 30 cm.

Simulations were conducted for two years of climatological data from Jokioinen, Finland. Year 1981 was a wet year (rainfall and snowmelt 792 mm, potential evapotranspiration 354 mm) and 1983 a dry year (610 mm and 412 mm, respectively). Accumulation and melting of snow was included using the same subroutine for both DRAINMOD and solutions to Richards equation.

Methods of comparison

Simulations were conducted with both DRAINMOD and the Richards equation model for both years on each soil. Daily drainage flows, water table depth, vertical fluxes in the profile, soil water content profiles at the end of each day, concentration of drainage water and daily leaching from drains (= concentration*flux) as predicted by the two models were compared. Moreover, the cumulative water balance terms (drainage flow, surface runoff and actual evapotranspiration) and cumulative leaching from drains as calculated by the two models were compared. Predicted results for each variable were plotted against each other; a linear regression was conducted and the correlation coefficient determined. The regression equation assumed was

$$DM = a \cdot RE + b$$

where DM is the value of the variable predicted by DRAINMOD, RE is the value predicted by Richards equation, and a and b are the slope and intercept of the regression equation. Perfect agreement between the two methods would result in a = 1.0 and b = 0.0 and a correlation coefficient, r = 1.0.

In addition to this correlation the average, maximum and minimum of the predicted daily values of each variable were compared. Moreover, the concentration profiles for days 120 (soon after snowmelt period), 240 (at the end of summer) and 360 are shown for selected soils.

RESULTS AND DISCUSSION

Comparisons between predictions by DRAINMOD (DM) and the Richards equation model (RE) are given in Tables 2-5 for the four soils considered and summary of cumulative hydrologic variables and cumulative leaching from drains is given in Table 6 for the four soils considered. In general there was excellent agreement between predictions by the two methods. The best agreement was obtained for the sandy soil. This was expected because DRAINMOD assumes hydrostatic or "drained to equilibrium" conditions above the water table and this assumption is best for soils with high hydraulic conductivities. The worst agreement between DRAINMOD and Richards equation model was obtained for the clay soil where "drained to equilibrium" assumption is a source of errors during snowmelt, heavy rainfall and long dry periods.

Results for the sandy soil:

According to Table 2, the agreement between the two methods for the sandy soil is excellent with correlation coefficients of r generally over 0.98. The lowest correlation coefficient was obtained for the dry year 1983 indicating that for longer evaporative conditions the flux computation of DRAINMOD need to be improved. The influence of flux computations on the calculated solute

Computed Drainage Flow (cm/d)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.983	0.978	0.004	0.143	0.144	0.000	0.006	0.897	0.864
83	0.998	1.026	0.000	0.078	0.080	0.000	0.000	0.589	0.589

Computed Water Table Depth (cm)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.994	0.982	1.443	84.4	84.3	33.1	30.1	102.3	99.4
83	0.996	0.921	6.439	98.1	96.8	50.0	50.0	133.2	129.5

Computed Vertical Fluxes in the Profile (0-100 cm) (cm/d)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.938	1.009	-0.011	0.139	0.130	-0.135	0.151	0.927	0.929
83	0.883	1.128	-0.021	0.080	0.069	0.168	0.221	0.602	0.681

Computed Water Content Profile (0-80 cm) (m^3/m^3)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.993	0018	-0.014	0.320	0.312	0.174	0.150	0.459	0.459
83	0.984	1.047	0.021	0.284	0.276	0.082	0.056	0.459	0.459

Computed Concentration in Drainage Water (mg/l)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.985	1.118	-0.670	4.965	4.881	1.000	0.000	5.950	5.930
83	0.998	0.986	-0.004	3.333	3.283	0.000	0.000	5.760	5.500

Computed Daily Leaching from Drains (kg/ha/d)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.977	0.964	0.002	0.070	0.069	0.000	0.000	0.513	0.503
83	0.996	1.021	-0.000	0.040	0.040	0.000	0.000	0.266	0.288

Table 2. Summary of results for the sandy soil (Ks = 4.0 cm/hr)

concentration profile are shown in Fig. 1 for both years. Results for the sandy soil for wet year 1981 are very good with almost exact agreement between predictions by the two methods. Summer 1983 was a relatively dry one and continuous upward flux increased the solute concentration in the rooted zone between days 120 and 240 (Fig. 1 b). There can be seen a small difference between the predictions of the two models for solute concentration in the rooted zone for day 240, but the difference in the concentration profile is very small at the end of the year (day 360).

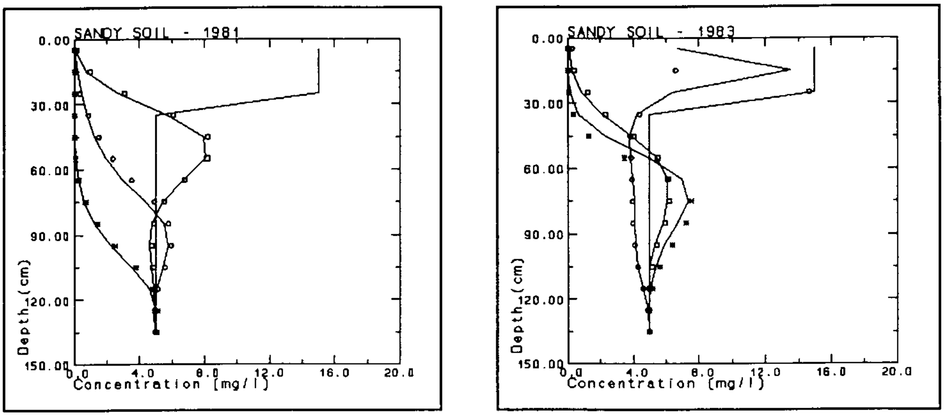

Figure 1. Solute concentration profiles for the sandy soil as predicted by Richards equation model and DRAINMOD for day 120 (squares), day 240 (circles) and 360 (stars). Calculated values of DRAINMOD indicated by continuous lines. Initial profile: 15 mg/l between 0-30 cm and 5 mg/l below 30 cm.

Results for the fine sand

There was an excellent agreement between the predictions of Richards equation model and DRAINMOD for the fine sand (Table 3.) with the exception of vertical fluxes in the profile (r = 0.888 for wet year and 0.760 for dry year). An example of water balance calculations is given in Fig. 2 where water table depth predicted the the two models is shown for wet year 1981. The results show almost ecaxt agreement between the two methods.

Computed vertical fluxes are on the average of the same magnitude (e.g. 0.118 cm/d for Richards equation and 0.111 cm/d for DRAINMOD for wet year 1981). However, DRAINMOD predicted both too large positive (downward) flux and too high negative (upward) flux. The reason for this is that DRAINMOD assumes that "drained to equilibrium" is reached immediately whereas actually there is a lag in the water table response until e.g. the wetting front reaches the initial water table.

Due to the fact that average fluxes calculated by DRAINMOD are very close to fluxes computed by Richards equation model, the computed concentration profiles (Fig. 3) for the three selected days (120, 240 and 360) are in good agreement between the two methods. DRAINMOD gives poorer results for dry year 1983 but the agreement is still very good indicating that the upward flux and dry zone assumptions are valid approximations if the saturated hydraulic conductivity is high enough.

Computed Drainage Flow (cm/d)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.955	0.971	0.008	0.122	0.127	0.000	0.017	0.808	0.829
83	0.986	0.986	0.008	0.069	0.076	0.000	0.000	0.350	0.328

Computed Water Table Depth (cm)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.967	0.939	3.963	76.1	75.4	0.0	0.0	100.2	95.4
83	0.956	0.891	7.076	92.2	89.2	43.5	45.6	133.8	131.1

Computed Vertical Fluxes in the Profile (0-100 cm) (cm/d)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.888	1.087	-0.017	0.118	0.111	-0.060	-0.133	0.667	0.712
83	0.760	1.199	-0.020	0.073	0.067	-0.058	-0.456	0.646	0.731

Computed Water Content Profile (0-80 cm) (m3/m3)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.956	1.079	-0.031	0.272	0.262	0.094	0.080	0.365	0.364
83	0.945	1.039	-0.016	0.243	0.236	0.037	0.036	0.364	0.364

Computed Concentration in Drainage Water (mg/l)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.919	1.139	-0.943	5.116	4.886	1.000	0.000	6.600	6.350
83	0.985	0.950	0.041	3.913	3.759	0.000	0.000	7.160	6.440

Computed Daily Leaching from Drains (kg/ha/d)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.946	0.910	0.004	0.061	0.059	0.000	0.000	0.402	0.404
83	0.983	0.954	0.004	0.038	0.041	0.000	0.000	0.225	0.204

Table 3. Summary of results for the fine sand (Ks = 2.0 cm/hr)

Results for loess loam

The results for the loess loam are given in Table 4 indicating that the water balance components predicted by Richards equation model and DRAINMOD are in good agreement. The only exception is, as discussed earlier, vertical fluxes especially for the dry year 1983.

Computed vertical fluxes predicted by the two methods deviate from each other by less than 10 %. Again, DRAINMOD predicted both too large positive flux and too high negative flux. The computed concentration profiles predicted by the two methods are given in Fig. 4 for the three selected days (120, 240 and 360).

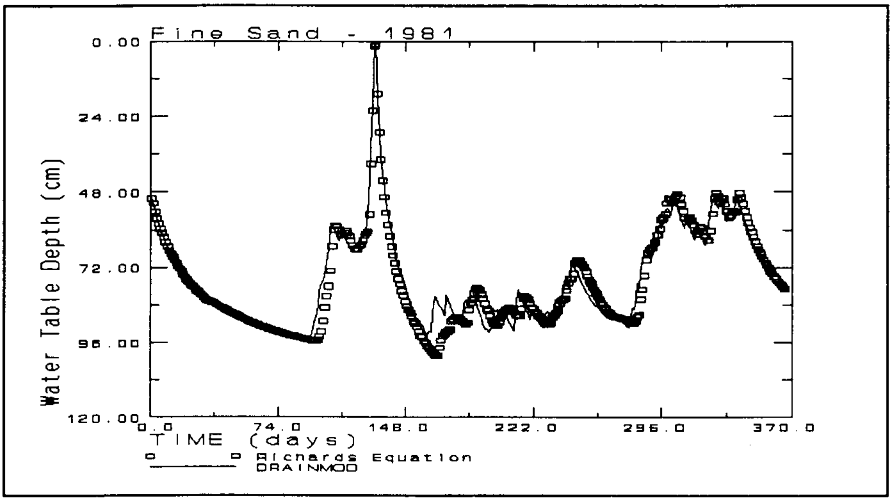

Figure 2. Water table depth predicted by Richards equation model and DRAINMOD for the fine sand and for wet year 1981.

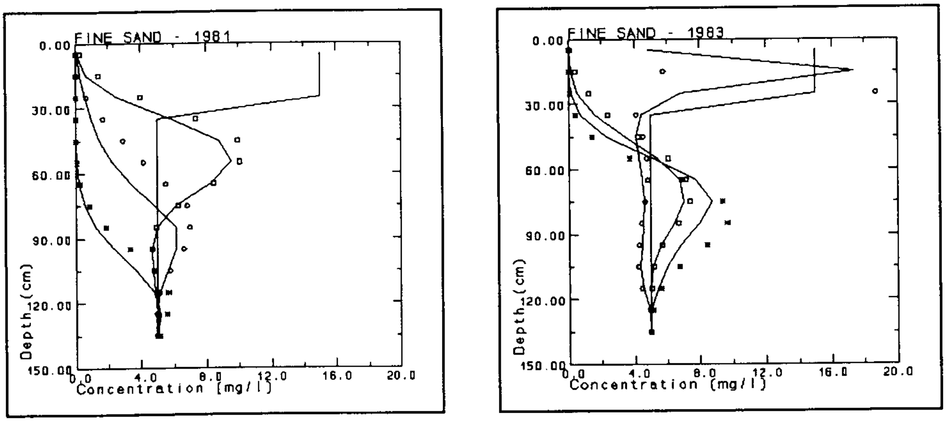

Figure 3. Solute concentration profiles for the fine sand as predicted by Richards equation model and DRAINMOD for day 120 (squares), day 240 (circles) and 360 (stars). Calculated values of DRAINMOD indicated by continuous lines. Initial profile: 15 mg/l between 0-30 cm and 5 mg/l below 30 cm.

The results for wet year 1981 are in good agreement between the two methods. For dry year DRAINMOD gives poorer results indicating that the upward flux and dry zone assumptions do not provide accurate flux computations for dry conditions if the saturated hydraulic conductivity is relatively low (0.6 cm/h = 14.4 cm/d).

Computed Drainage Flow (cm/d)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.964	0.953	0.009	0.104	0.107	0.000	0.016	0.357	0.437
83	0.975	1.027	0.005	0.058	0.065	0.000	0.000	0.358	0.437

Computed Water Table Depth (cm)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.972	0.904	4.981	66.4	65.0	0.0	0.0	106.1	92.0
83	0.962	0.807	10.61	88.4	81.9	0.0	0.0	145.4	125.6

Computed Vertical Fluxes in the Profile (0-100 cm) (cm/d)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.895	0.994	- 0.006	0.097	0.090	- 0.070	- 0.087	0.398	0.576
83	0.805	1.027	- 0.009	0.063	0.056	- 0.059	- 0.136	0.516	0.485

Computed Water Content Profile (0-80 cm) (m3/m3)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.941	1.130	- 0.059	0.401	0.394	0.220	0.185	0.456	0.455
83	0.911	1.123	- 0.053	0.373	0.366	0.142	0.126	0.456	0.455

Computed Concentration in Drainage Water (mg/l)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.882	0.763	1.149	5.394	5.264	1.000	0.000	6.810	6.720
83	0.994	0.973	0.062	3.945	3.900	0.000	0.000	7.310	6.690

Computed Daily Leaching from Drains (kg/ha/d)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.962	0.898	0.005	0.059	0.058	0.000	0.000	0.232	0.260
83	0.970	1.004	0.003	0.033	0.036	0.000	0.000	0.231	0.265

Table 4. Summary of results for loess loam (Ks = 0.6 cm/hr)

Results for the clay soil

The assumption of "drained to equilibrium" assumption can be expected to be a source of errors for soils of low hydraulic conductivity. The results of Table 5 partly support this expectation. However, for the wet year 1981 the water balance and transport of solutes are in suprisingly good agreement between the two methods. Computed water table depth for the wet year as predicted by the two methods is shown in Fig. 5 indicating very good agreement.

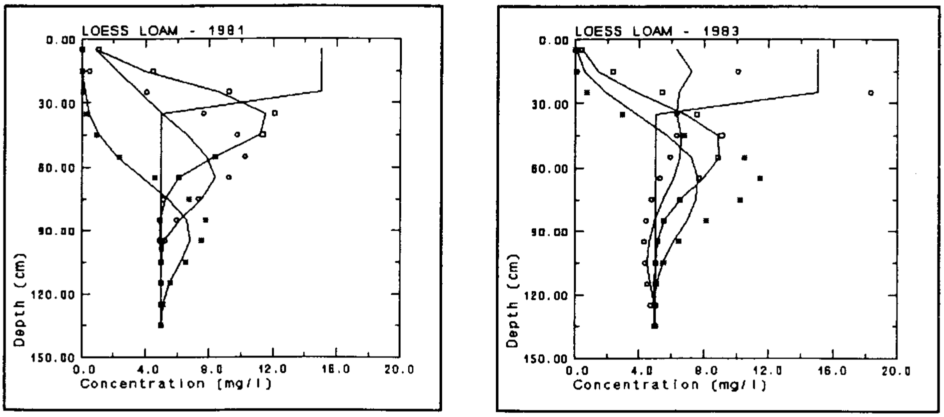

Figure 4. Solute concentration profiles for the loess loam as predicted by Richards equation model and DRAINMOD for day 120 (squares), day 240 (circles) and 360 (stars). Calculated values of DRAINMOD indicated by continuous lines. Initial profile: 15 mg/l between 0-30 cm and 5 mg/l below 30 cm.

Volumetric water content at three depths (10, 30 and 50 cm) as predicted by the two methods is shown in Fig. 6. Due to the fact that DRAINMOD assumes a "drained to equilibrium" profile below the rooted zone, water content calculated by DRAINMOD usually tends to be too low in the rooted zone (at depths 10 and 30 cm) and too high below the rooted zone (at 50 cm depth). The difference between the water content values predicted by Richards equation model and DRAINMOD was greatist for the clay soil and for the dry year 1983 (Fig. 6).

Solute concentration profiles as calculated by Richards equation model and DRAINMOD are shown for days 120, 240 and 360 and for both years in Fig. 7. The predicted profiles are very close to each other for the wet year and for day 120, but for day 240 the peak concentration as predicted by Richards equation model is much higher than concentration calculated by DRAINMOD. For the dry year 1983 the results are even poorer indicating that the dry zone concept used by DRAINMOD produces on the average too low upward fluxes as compared to Richards equation model and this results in a too low solute concentration in the rooted zone after a long evaporation period (results for day 240 in Fig. 7).

Summary of cumulative variables

A summary of the hydrologic variables and cumulative leaching from drains for all soils is given in Table 6. For sandy soil and fine sand the cumulative values as predicted by the two methods are in very good agreement. For loess loam and clay soil DRAINMOD overpredicts drainage flow and leaching from drain and calculates lower actual transpiration rates especially for the dry year 1983.

Computed Drainage Flow (cm/d)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.959	0.974	0.007	0.052	0.057	0.000	0.000	0.160	0.160
83	0.866	0.962	0.011	0.035	0.045	0.000	0.000	0.160	0.160

Computed Water Table Depth (cm)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.952	0.818	4.318	61.7	54.8	0.0	0.0	133.1	103.4
83	0.871	0.864	0.175	82.4	71.4	1.0	0.0	135.0	145.9

Computed Vertical Fluxes in the Profile (0-100 cm) (cm/d)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.820	0.705	0.009	0.051	0.045	- 0.074	- 0.068	0.397	0.380
83	0.703	0.923	- 0.001	0.040	0.036	- 0.054	- 0.315	0.308	0.630

Computed Water Content Profile (0-80 cm) (m^3/m^3)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.928	1.170	- 0.074	0.429	0.427	0.245	0.223	0.454	0.453
83	0.894	1.032	- 0.011	0.410	0.412	0.213	0209	0.454	0.453

Computed Concentration in Drainage Water (mg/l)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.950	0.769	1.087	5.608	5.402	0.000	0.000	7.640	6.900
83	0.986	0.939	0.155	4.184	4.086	0.000	0.000	8.010	6.860

Computed Daily Leaching from Drains (kg/ha/d)

YEAR				RE	DM	RE	DM	RE	DM
	r	a	b	av	av	min	min	max	max
81	0.986	0.895	0.004	0.034	0.034	0.000	0.000	0.122	0.110
83	0.849	0.897	0.007	0.022	0.027	0.000	0.000	0.122	0.105

Table 5. Summary of results for the clay soil (Ks = 0.1 cm/hr)

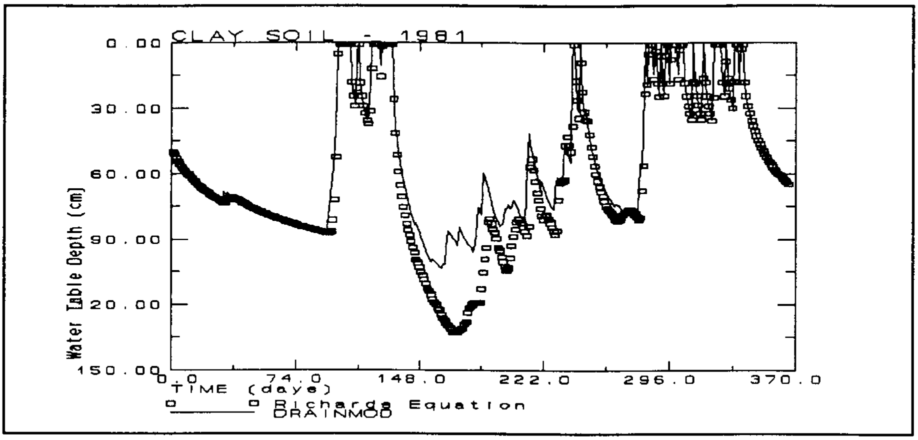

Figure 5. Water table depth predicted by Richards equation model and DRAINMOD for the clay soil and for wet year 1981.

Cumulative Drainage Flow (mm)

	Sand		Fine Sand		Loess L.		Clay Soil	
YEAR	RE	DM	RE	DM	RE	DM	RE	DM
81	522	521	446	459	378	391	190	209
83	285	288	251	276	211	233	130	166

Cumulative Surface Runoff (mm)

	Sand		Fine Sand		Loess L.		Clay Soil	
YEAR	RE	DM	RE	DM	RE	DM	RE	DM
81	0	0	34	21	74	65	256	245
83	0	0	0	0	9	0	88	86

Cumulative Actual Evaporation (mm)

	Sand		Fine Sand		Loess L.		Clay Soil	
YEAR	RE	DM	RE	DM	RE	DM	RE	DM
81	354	354	354	354	354	354	353	344
83	411	408	412	412	407	394	399	360

Cumulative Leaching from Drains (kg/ha)

	Sand		Fine Sand		Loess L.		Clay Soil	
YEAR	RE	DM	RE	DM	RE	DM	RE	DM
81	25.8	25.3	22.5	21.8	21.6	21.3	12.2	12.5
83	14.7	14.6	14.1	14.9	12.1	13.2	8.2	9.9

Table 6. Summary of hydrologic variables and cumulative leaching from drains as predicted by Richards equation model (RE) and DRAINMOD (DM) for the four soils for wet (1981) and dry (1983) years at Jokioinen, Finland.

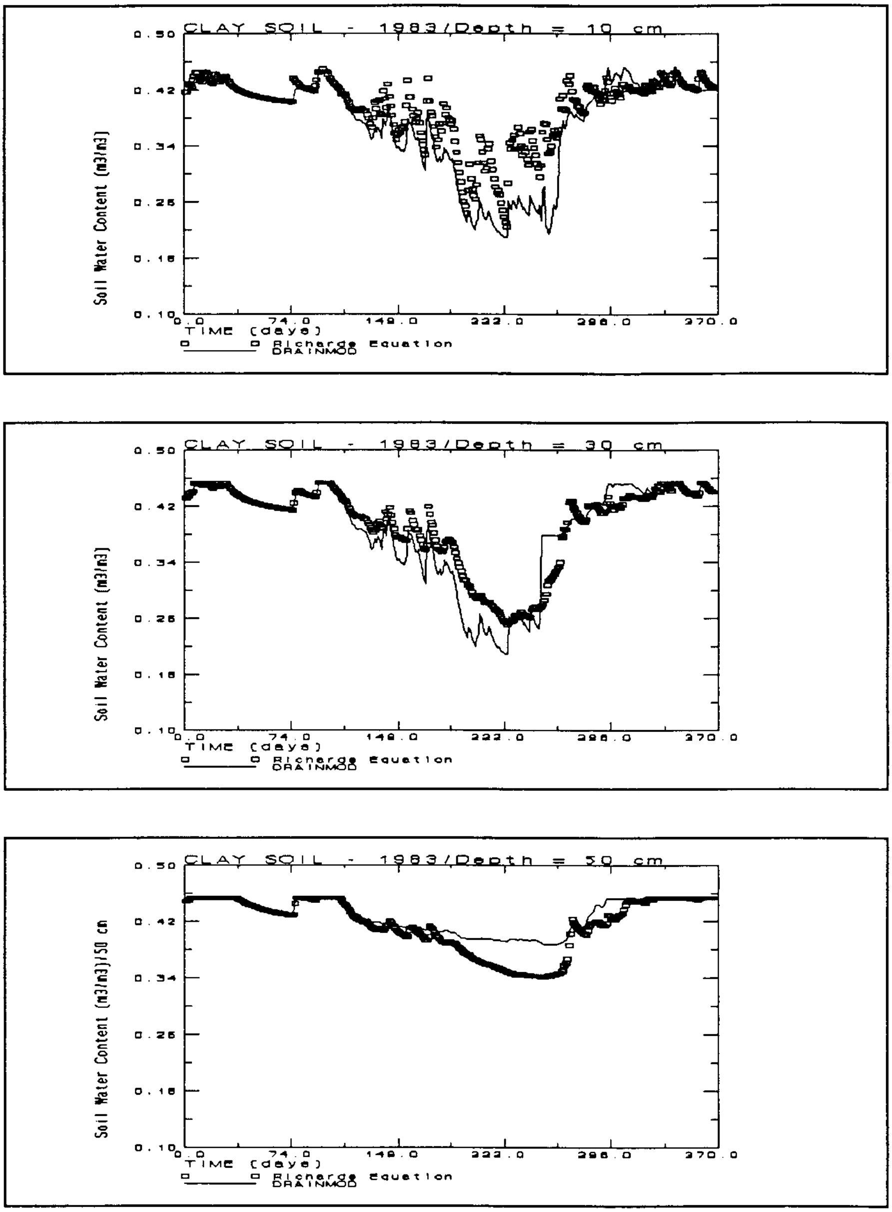

Figure 6. Volumetric water content at three depths (10, 30 and 50 cm) as predicted by Richards equation model and DRAINMOD for the dry year 1983.

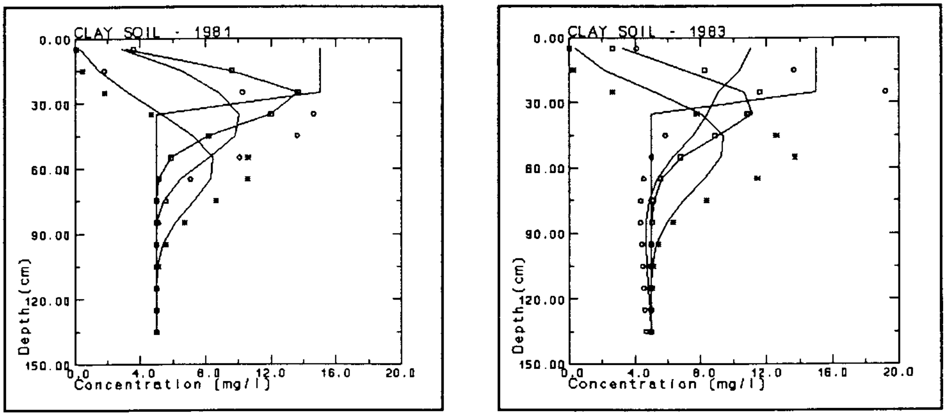

Figure 7. Solute concentration profiles for the clay soil as predicted by Richards equation model and DRAINMOD for day 120 (squares), day 240 (circles) and 360 (stars). Calculated values of DRAINMOD indicated by continuous lines. Initial profile: 15 mg/l between 0-30 cm and 5 mg/l below 30 cm.

SUMMARY

The purpose of this paper is to provide comparisons between predictions by two different models: the numerical solution of the Richards equation and DRAINMOD. Predictions by both models were compared for two climatological years (wet and dry) on four soils. Because DRAINMOD is based on the assumption that the unsaturated profile is in equilibrium with the water table, it does not predict time lags of fluxes and water table response as given by the Richards equation. However, predicted results by the two models were generally in good agreemet both for water balance components and for solute transport (convection only) variables. Analysis of the results presented herein indicate that fluxes and solute transport can be estimated very reliably for soils with high hydraulic conductivity (sandy soil and fine sand in this study). Fluxes and solute transport as predicted by DRAINMOD differ most from results of Richards equation models for dry conditions and for soils with low hydraulic conductivity, i.e. loess loam and clay soil in this study. For wet year the agreement between predictions by the two models was good even if the soil hydraulic conductivity is was low.

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Session 3 - *3^{e} session*

Water Table Management Effects on Crop Productivity and Water Quality

Effets de la gestion de nappe sur la productivité agricole et la qualité de l'eau

STRESS DAY INDEX MODELS TO PREDICT CORN AND SOYBEAN YIELD RESPONSE TO WATER TABLE MANAGEMENT

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ABSTRACT. Drainage and related agricultural water table management systems are being designed in humid regions of the United States using the water management simulation model, DRAINMOD. Since excessive and deficient soil-water conditions are stressful to most crops, crop yield is a useful measure of the effectiveness of the water management system design. Stress day index (SDI) models are presented which can be used to predict corn and soybean yield response to excessive and deficient soil-water conditions. The relative yield - SDI models developed herein and SDI models reported in the literature were tested using a comprehensive data base developed from corn and soybean yield studies conducted in eastern North Carolina over the past 35 years.

RESUME ET CONCLUSIONS. Connaissances acquises: *Aux Etats-Unis, les systèmes de drainage des zones humides ainsi que les techniques de gestion du niveau de nappe qui y sont liées, ont été élaborés en utilisant le modèle de gestion DRAINMOD. Le rendement de la plupart des cultures est influencé par l'excès ou le déficit d'eau dans le sol. Le rendement d'une culture est donc une mesure utile pour apprécier l'efficacité d'un système de gestion d'eau. Des indices de stress hydriques (SDI) ont été développés pour quantifier la réduction de rendement due aux conditions de stress hydrique existant dans le sol. La méthode des SDI prend en compte d'une part, la mesure du degré (quantité) de stress imposé à la culture, et d'autre part, sa sensibilité au stress qui est fonction de l'espèce cultivée et de son stade de développement.*

Objectifs *- Le but de cette étude était triple. Premièrement, déterminer expérimentalement les facteurs de sensibilité culturale (CS) pour des cultures de maïs et de soja stressées par un excès d'eau dans le sol. Deuxièmement, développer des modèles d'indice de stress hydrique pour prédire le rendement de cultures de maïs et de soja soumises à des niveaux de nappe élevés, en se basant sur les facteurs CS déterminés expérimentalement. Troisièmement, tester à la fois les modèles SDI que nous avons développés pour un stress hydrique dû à un excès d'eau, ainsi que les modèles SDI mentionnés dans la littérature, pour prédire le rendement cultural en cas de stress provoqué par un déficit hydrique. Le rendement prédit (calculé) est comparé au rendement mesuré sur les sites d'expérimentation.*

Modèles d'indice de stress hydrique pour predire la variation de rendement du maïs et du soja en fonction de la gestion du niveau de nappe.

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***Protocole expérimental** - Les facteurs de sensibilité culturale ont été déterminés pour des plantes soumises à un excès d'eau durant cinq stades de leur développement physiologique. Les expérimentations ont été conduites en cases lysimétriques pour les cinq stades de développement physiologique déterminés à partir de la bibliographie. Les périodes de stress ont été déclenchées en remontant le niveau de la nappe à proximité de la surface du sol, une fois pendant dix jours consécutifs pour le maïs et une fois pendant sept jours consécutifs pour le soja, et ce pour chacun des cinq stades de développement retenus. Le maïs était plus sensible àl'excès d'eau juste avant le stade de formation des grains; le soja, durant les stades de développement et de remplissage de la gousse.*

Des modèles ont été proposés pour prédire le rendement relatif de cultures de maïs et de soja soumises à un niveau de nappe élevé. Ces modèles sont basés sur des analyses de régression faites à partir de données expérimentales obtenues dans l'état de l'Ohio. La durée des observations était de treize ans pour le maïs et de six ans pour le soja. Ces modèles utilisent l'indice de stress hydrique SDI, fonction des facteurs SEW_{30} *et CS. Le facteur* SEW_{30} *représente un critère du stress engendré par un niveau de nappe élevé. Le facteur CS est déterminé expérimentalement. Le modèle "maïs" a été validé avec des données provenant d'Inde et de Caroline du Nord; en utilisant la totalité des données, il expliquait 69 pourcent de la variance du rendement relatif. Le modèle "soja" expliquait 66 pourcent de cette variance pour les six années de données obtenues dans l'Ohio.*

Les modèles "rendement-SDI" que nous avons développés, et les modèles SDI de la littérature, ont été validés en utilisant une importante base de données issue des recherches menées sur le rendement des cultures de maïs et de soja dans l'est de la Caroline du Nord. Les expérimentations de terrain ont fourni l'équivalent de 94 observations pour le rendement du maïs, et de 128 observations pour le rendement du soja. Les stress hydriques journaliers, pour différentes conditions climatiques, ont été simulés avec DRAINMOD. Préalablement à la simulation des rendements, les données d'entrée du modèle ont été vérifiées en comparant les niveaux de nappe simulés et observés pour 12 combinaisons sites-années. La réduction de rendement liée à un stress hydrique (excès ou déficit), ainsi que le retard des semis, ont été simulés.

***Résultats** - Douze modèles SDI ont été comparés et validés pour le maïs. Tous les modèles testés ont fourni un relativement bon ajustement avec les 94 données relatives au rendement du maïs: l'erreur moyenne variait de -0.1 pour-cent à -6.1 pour-cent. L'erreur moyenne augmentait lorsque l'on introduisait un facteur de pondération pour les périodes de déficit hydrique marqué. La corrélation calculée par rapport à la droite de pente 1:1, entre les rendements calculés et observés sur l'ensemble des données, variait de 66.6 à 79.5 pour-cent. Ceci laisse supposer que les méthodes de simulation étaient sensibles à la variation inter-annuelle du rendement, liée à la variabilité du stress hydrique.*

Le modèle "rendement soja-SDI" a fourni de relativement bonnes prédictions à long terme pour le calcul du rendement moyen: l'erreur moyenne était de -0.4 pour-cent. Cependant, le modèle n'était pas aussi fiable pour prédire la variation de rendement d'une année sur l'autre. La corrélation entre rendements simulés et observés, calculée par rapport àla droite de pente 1:1 , n'était que de 47.9 pour-cent. Les résultats de cette étude ont montré que des méthodes simples comme celles des SDI utilisant DRAINMOD pour simuler les conditions hydriques du sol, peuvent fournir des estimations du rendement moyen, sur de longues périodes, pour des cultures de maïs et de soja soumises à des niveaux de nappe élevés.

INTRODUCTION

Rainfall is extremely variable during the growing season in the southeastern U.S. It seldom occurs in an amount and distribution necessary to achieve high yields more often than about one year in ten. In other years, soil-water, either too much and/or too little, is usually the single most limiting factor for high yields (Sopher, 1969).

Yield reductions often develop from stresses caused by excessive soil-water conditions on poorly drained soils. The yield reductions may result either (1) from the inability to plant and tend the crop at the right time due to poor trafficability or (2) from direct damage to the crop due to a lack of oxygen (anaerobiosis); biochemical toxicity; and/or nutrient deficiencies; resulting from an elevated water table or excessive soil-water condition. Although annual rainfall exceeds evapotranspiration on the average, droughts ranging from a few days up to several weeks occur in many years between June and September. While excessive soil-water is a major concern, substantial yield reductions resulting from deficient soil-water conditions occur frequently, even on poorly drained soils.

The primary purposes of agricultural water management systems are to increase production efficiency and yield reliability by improving the soil-water environment. Crop yield is a practical measure of crop response to water stresses for the purpose of optimizing the water management system design. The stress-day-index (SDI) approach (Hiler, 1969) was developed to quantify the cumulative effect of stresses imposed on a crop throughout the growing season.

Evans et al. (1990) reported crop susceptibility factors for corn and soybean stressed by excessive soil-water conditions. Using these crop susceptibility factors and field data from Ohio, Evans et al. (1991) developed yield - SDI relationships to estimate corn and soybean yield response to excessive soil water conditions. Evans and Skaggs (1992) tested these yield - SDI relationships along with other SDI models reported in the literature against corn and soybean yields observed in field experiments conducted in eastern North Carolina. The purpose of this paper is to summarize the Stress Day Index relationships developed and tested in North Carolina.

STRESS DAY INDEX APPROACH

The general form of the SDI concept described by Hiler (1969) may be expressed

$$SDI_X = \sum_{i=1}^{n} SD_i \ CS_i \tag{1}$$

where n is the number of growth periods (distinct stages of physiological development) and SD and CS are stress day and crop susceptibility factors for period i, respectively. The subscript x has been added herein and when replaced by w, d, or p is used to denote the specific yield reducing condition, either wet, dry or planting delay, respectively.

Stress Day Factor

The stress day factor (SD) is a measure of the intensity and duration of stress. Sieben (1964) related crop response to fluctuating water tables using so-called SEW_{30} values computed from

$$SEW_{30} = \sum_{i=1}^{n} 30 - x_i \qquad (2)$$

where x_i is the water table depth below the soil surface on day i, and n is the number of days in the period being considered. Negative terms inside the summation are neglected such that the summation is a measure of the exceedence of some critical water table depth. Sieben (1964) assumed the critical depth to be 30 cm, so the SEW_{30} value has units of cm-days.

Shaw (1974) related corn yield to deficient soil-water conditions. He defined a stress day factor based on 5-day evapotranspiration (ET) deficient computed as

$$SD_i = WF \times \sum_{j=1}^{5} 1 - ET_{ij} / PET_{ij} \qquad (3)$$

where SD_i was the stress factor for period i, ET_{ij} was the actual evapotranspiration that occurred in period i, on day j, and PET_{ij} was the potential evapotranspiration in period i, on day j. The SD_i was computed for 5-day intervals beginning 40 days prior to silking and ending 44 days after silking for a total of 17 5-day periods. Whenever the stress day factor for two or more consecutive 5-day periods was greater than 4.5, (maximum possible value is 5.0) a severe stress weighting factor (WF in equation 3) of 1.5 was used; otherwise, the WF was 1.0.

Skaggs et al. (1982) developed a relationship to estimate the effect of planting date delay on corn yield. Their relationship was developed from non-irrigated planting date studies presented by Krenzer and Fike (1977). Seymour et al. (1992) conducted similar planting date studies on a field with subirrigation. After combining results of the two studies, Seymour et al. (1992) defined the plant delay stress day factor as the number of days planting was delayed past an "optimum" date for a given location.

Crop Susceptibility Factor

The crop susceptibility factor is a measure of the crop susceptibility to a unit of stress and is a function of crop species and its stage of development. The crop susceptibility factor is determined experimentally by subjecting the crop to a critical level of stress during each discrete physiological growth stage and measuring the yield response. The crop susceptibility factor for each growth stage as defined by Hiler (1969) is computed by

$$CS_i = \frac{X - X_i}{X} \qquad (4)$$

where X_i is the harvested crop yield when subjected to the critical stress at growth stage i and X is the crop yield when no stress is applied. Crop susceptibility factors have been reported for a few crops (Desmond et al., 1985; Evans et al., 1990; Evans, 1991; Hiler and Clark, 1971; Mukhtar et al., 1990; Ravelo et al., 1982; Seymour et al., 1992; Shaw, 1974; Sudar et al., 1979).

Evans et al. (1990) reported crop susceptibility factors determined for corn and soybean plants stressed by excessive soil-water conditions during six physiological growth stages. Experiments were conducted using lysimeters with stress periods induced by raising the water table to the soil surface once for ten consecutive days for corn and for seven consecutive days for soybean. Their results are summarized in Table 1.

Shaw (1974) developed crop susceptibility factors to relate corn yield to deficient soil-water conditions, Table 2. Shaw's values were developed from controlled experiments conducted by Denmead and Shaw (1960); Wilson (1968); Classen and Shaw (1970); and Mallett (1972). For periods other than shown in Table 2, a susceptibility factor of zero (0) is used.

Soybean yield response to dry stress has been reported in several studies (Brown et al., 1985; Hiler et al., 1974; Sepaskhah, 1977; Sionit and Kramer, 1977; Smajstrla and Clark, 1982; Snyder et al., 1982). Evans et al. (1986) compared susceptibility factors determined from these studies and found them to be quite variable. Sudar et al. (1979) estimated soybean CS values for Iowa from the literature. While not specifically stated, the values reported by Sudar were likely developed for indeterminate varieties typically grown in the Midwestern U.S. Evans (1991) combined the results reported by Sudar with other data in the literature to develop CS values to estimate the sensitivity of determinate variety soybean to dry stress. The estimates reported by Evans (1991) and used herein are summarized in Table 3.

		Period During Growing Season CS Values Used		
CORN Growth Stage[#]	Development[&] Stage	Start	Stop	CS Factors
	Days After Planting ------ DAP -------			
Establishment	Stage 1	0	29	0.20
Vegetative (rapid growth)	Stage 2	30	49	0.22
Late Vegetative	Stage 3-4	50	69	0.32
Flowering (pollination)	Stage 5-6	70	89	0.19
Yield Formation	Stage 7-8	90	109	0.08
Ripening	Stage 9-10	110	130	0.02[+]
SOYBEAN	Stage[@]			
Establishment	V0-V4	0	24	0.19
Vegetative	V5-V13	25	54	0.13
Flowering	V14-V17/R1-R2	55	74	0.19
Pod Development	R3-R4	75	94	0.26
Pod Filling	R5	95	109	0.25
Ripening				
(Pods w/full size beans)	R6	110	124	0.08
(Pods yellowing)	R7	125	134	0.01
(Pods brown)	R8	135	145	0.00

[#] After Doorenbos and Kassam (1979).

[&] Refers to stage of corn development as described by Hanway (1963).

[@] Refers to stage of soybean development described by Fehr et al. (1971).

[+] Value estimated from graph of corn CS values versus DAP.

[^] Values estimated from graph of soybean CS values versus DAP.

Table 1. Growth stage and CS values used to develop SDI relationships for excessive soil-water stresses (eq. 9 for corn, eq. 12 for soybean). (After Evans et al., 1990)

	Growing period*			
Period#	Relative to planting		Relative to silking	CS
	--------------- Days -------------			
	0 to 39			0.0
-8	40 to 44		-40 to -36	0.5
-7	45 to 49		-35 to -31	0.5
-6	50 to 54		-30 to -26	1.0
-5	55 to 59		-25 to -21	1.0
-4	60 to 64		-20 to -16	1.0
-3	65 to 69		-15 to -11	1.0
-2	70 to 74		-10 to -6	1.75
-1	75 to 79		-5 to -1	2.0
0	80		50% silked	
+1	80 to 84		0 to +4	2.0
+2	85 to 89		+5 to +9	1.3
+3	90 to 94		+10 to +14	1.3
+4	95 to 99		+15 to +19	1.3
+5	100 to 104		+20 to +24	1.3
+6	105 to 109		+25 to +29	1.3
+7	110 to 114		+30 to +34	1.2
+8	115 to 119		+35 to +39	1.0
+9	120 to 124		+40 to +44	0.5
	125 to black layer		+45 to maturity	0.0

* Days relative to planting are based on the typical medium maturity variety (1500 GDD (growing degree days °F) to silking or comparative relative maturity, CRM, group 114 to 116) grown under eastern N.C. conditions and planted on April 10. Early maturity varieties (1350 to 1500 GDD to silking, CRM 100 to 114) will silk 1 to 5 days sooner than shown. Late maturity varieties (1500 to 1700 GDD to silking, CRM 116-130) will silk 1 to 5 days later than shown. On average, the number of calendar days to silking decreases as planting is delayed past April 10.

Value represents 5-day periods relative to silking as reported by Shaw.

Table 2. Crop susceptibility factors used in eq. 10 to evaluate deficient soil-water conditions on corn yield. (After Shaw, 1974).

DEVELOPMENT OF STRESS DAY INDEX MODELS

Once the crop susceptibility factors are known, the relationship between crop yield and SDI can be determined for a given type of stress (excess, deficient, plant delay) from experimental data using regression analysis to relate yield to the actual soil-water conditions (Stress Day Factor). These experimental data should be different from those used to determine the CS factors. The generalized yield SDI relationship determined from simple linear regression is given by:

$$Y_i = Y_p - a\ SD_i \qquad (5)$$

Stage of Development	Duration of Period	Crop Susceptibility
	DAP	
Plant to V5	0 - 32	0.01
V5 - V15	32-74	0.03
V15(R1) - V17	74 - 81	0.05
R2 (early)	81 - 91	0.10
R2 (late)	91 - 102	0.15
R3 - R4	102 - 115	0.20
R5	115 - 133	0.10
R6 (early)	133 - 146	0.05
R6 (late)	146 - 160	0.02
R7	160 - 170	0
R8	170	0

* Values shown are for Group VI maturity. Plant to R1 occurs about 5-10 days sooner for Group V varieties and 5-10 days later for Group VII varieties. The period R3 to R7 is typically 55 to 60 days, regardless of planting date. In North Carolina, plant delays reduce the length of the time from planting to R3 by about 1 day for each 2 days delay in planting up to June 15. From June 15 to July 5, the ratio is about 1:3, after July 5, the ratio is about 1:4.

Table 3. Crop susceptibility values used in eq. 13 to relate soybean yield (determinate varieties) to deficient soil water stresses. (After Sudar et al., 1979; Evans, 1991).

where Y_i is the actual yield (kg/ha) observed in year i, Y_p is the potential or base maximum yield that would occur in the absence of any soil-water related stress, a is the yield reduction per unit of SDI (slope of regression line). The SDI_i is computed from equation 1 using the appropriate CS values from Tables 1, 2 or 3 and equation 2 or 3 to compute the SD factor. When expressed in terms of actual yield, Y_i, Y_p, and a are site dependent, influenced by a variety of factors including soil, climate, fertility, crop variety, etc. The influence of these factors can be minimized by normalizing equation 5 to

$$RY_i = Y_i/Y_p = 1 - b\ SD_i \qquad (6)$$

where RY_i is the relative yield, which when multiplied by 100, is expressed as a percent of potential yield, Y_p; and b is the RY reduction per unit of SDI. Equation 6 is more universal than equation 5 because the Y_p accounts for the influence of soil, climate, fertility, and crop variety.

Evans et al (1991) developed yield - SDI models to relate corn and soybean yields to excessive soil-water conditions. The relative yield models were based on SDI relationships using SEW_{30} (0.3-m water table depth) to describe the high water table stress criteria and the CS factors determined in studies conducted in North Carolina (Table 1). The models were developed using existing field data for SDI and corn and soybean yield data from Ohio. The corn model was tested against data from India and North Carolina and explained 69 % of the relative yield variance for the pooled data, Figure 1. The soybean model explained 66 % of the variance in relative yield for six years of soybean data from Ohio, Figure 2.

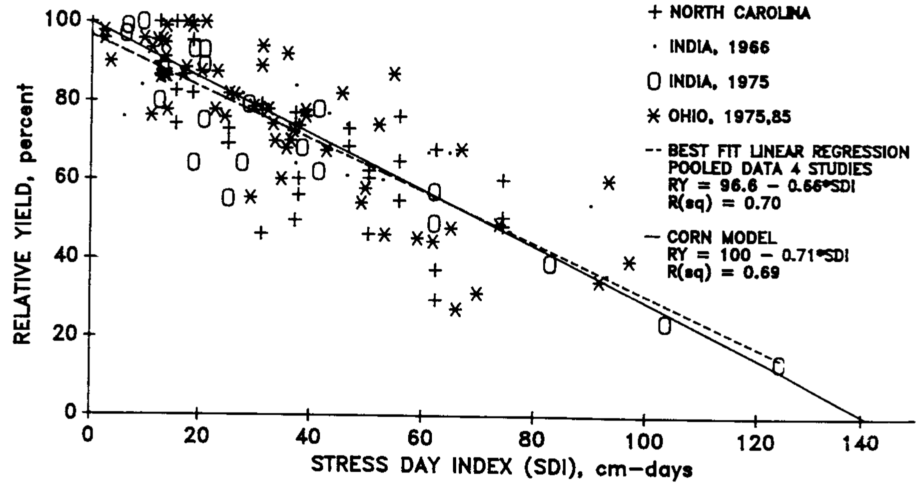

Figure 1. Corn yield SDI model developed from linear regression of corn data from Ohio (Schwab et al., 1975,1985) and CS values from North Carolina. (After Evans et al., 1991)

Using similar procedures, yield - SDI models have been developed to relate corn yield to deficient soil-water conditions (Shaw, 1974) and to planting date delays (Seymour et al, 1992). Combining data from the literature with SDI results presented by Sudar et al. (1979), Evans (1991) developed a yield - SDI model to relate soybean yield to deficient soil-water conditions. Using data from a 3-year study reported by Fike (1974), Evans (1991) developed a yield - SDI model to relate soybean yield to planting delays. The above relationships and submodels are summarized in Table 4.

TESTING AND VALIDATION OF STRESS DAY INDEX MODELS

The water management simulation model, DRAINMOD, (Skaggs, 1978) simulates soil-water conditions in high water table soils. The model considers rainfall, infiltration, surface runoff, drainage, storage and deep seepage to perform a water balance for the soil profile. Hardjoamidjojo and Skaggs (1982) incorporated approximate methods based on the stress-day-index concept to predict corn yield response to stresses caused by excessive and deficient soil-water conditions. The general crop response model represented by these modifications was described by Skaggs et al. (1982) as

$$RY = RY_w \, RY_d \, RY_p \qquad (7)$$

where RY is the overall relative yield for a given year, RY_w is the relative yield that would be obtained if only wet stresses occurred, RY_d is the relative yield that would be obtained if only dry stresses occurred, and RY_p is the relative yield resulting from planting delays only.

Stress	Submodel	Equation No.	Reference	Stress day Factor	Reference	Crop Susceptibility	Reference
CORN							
Wet	$RY_w = 100 - 0.71{*}SDI_w$ $RY_w = 0$	$SDI \leq 141$ (9a) $SDI > 141$ (9b)	9	SEW_{30} (eq. 2)	37	6 stages	8
Dry	$RY_d = 100 - 1.22{*}SDI_d$ $RY_d = 0$	$SDI < 82$ (10a) $SDI \leq 82$ (10b)	32 normalized by 16	1-(AET/PET) (eq. 3)	32	17 5-day stages	32
Plant Delay	$RY_p = 100 - 0.88{*}PD$ $RY_p = 130 - 1.60{*}PD$ $RY_p = 0$	$PD < 40$ (11a) $40 \leq PD \leq 80$ (11b) $PD > 80$ (11c)	31 after 21	Plant Delay Past Optimum (April 15)	31 after 21	2 stages	31, 21
SOYBEAN							
Wet	$RY_w = 100 - 0.65{*}SDI_w$ $RY_w = 0$	$SDI \leq 154$ (12a) $SDI > 154$ (12b)	9	SEW_{30} (eq. 2)	37	6 stages	8
Dry	$RY_d = 100 - 7.2{*}SDI_d$ $RY_d = 0$	$SDI < 13.9$ (13a) $SDI \leq 13.9$ (13b)	10 after 43	1-(AET/PET) (eq. 3)	43	10 stages	10 from literature
Plant Delay	$RY_p = 100 - 0.5{*}PD$ $RY_p = 140 - 1.8{*}PD$ $RY_p = 0$	$PD \leq 30$ (14a) $30 < PD \leq 78$ (14b) $PD > 78$ (14c)	10 after 13	Plant Delay Past Optimum (May 15)	10 after 13	2 stages	10 after 13

Under severe stress conditions, the relationship given by equation 5 over predicted yield for the Iowa data evaluated by Shaw (1974). Shaw investigated several methods of weighting the stress day factor (eq. 6). The best fit for the Iowa conditions was obtained when an additional weighting factor of 1.5 was applied to the SD factor whenever two or more consecutive 5-day SD factors were 4.5 or greater. The corn data presented herein are evaluated both with and without this severe stress dry weight factor.

Table 4. Relative yield - stress day index relationships used to predict corn and soybean yield response to excessive and deficient soil water conditions and to planting delays.

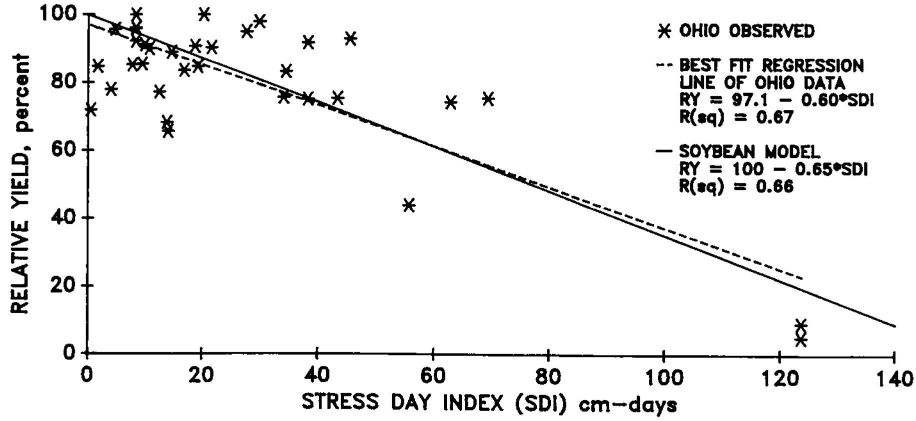

Figure 2. Soybean yield - SDI model developed from linear regression of soybean data from Ohio (Schwab, 1985) and CS values determined in North Carolina. (After Evans et al., 1991).

To compare predicted yields to field measured yields, relative yield may also be expressed as:

$$RY = Y/Y_0 \qquad (8)$$

where Y is the measured or observed yield for a given year and Y_0 is the yield that would have occurred in the absence of any soil-water related stresses. Y_0 refers to the base maximum yield that would occur for a consistent combination of agronomic inputs that were not limited by soil - water.

The relative yield components, RY_w, RY_d and RY_p, are assumed to be independent with individual submodels used to calculate each component. Each yield - SDI submodel should be developed and tested independently as discussed in the previous section. The validity of the generalized model (equation 7) should then be tested with field data comprising different types and amounts of soil-water stress.

Observed Yields (Field Validation Data)

Field experiments have been conducted on the Tidewater Research Station near Plymouth, N. C. for over 50 years. The soils at the Tidewater Station are poorly drained. Drainage of most fields has been improved by the installation of parallel ditches or drain tile/tubing so that the site is conducive for evaluation by DRAINMOD. The drainage intensity varies from field to field as discussed by Evans (1991). Even with improved drainage, soil wetness is a problem in some years resulting in planting delays and high water table conditions during the growing season. Droughty conditions develop during periods with below normal rainfall. Corn and soybean are the predominant crops grown on the station.

Five independent studies were identified that provided data suitable to evaluate the SDI relations presented in Table 4. The source and description of these yield data and soil, site, and drainage system parameters for each study were reported by Evans (1991).

Validation Procedure

Overall relative yield (equation 7) was predicted using DRAINMOD with equations 9, 10, and 11 to predict the individual corn yield components and equations 12, 13, and 14 to predict the individual soybean yield components. The corn yield relationship given by equation 10 was evaluated both with (Method 2) and without (Method 1) the severe-stress dry weight factor (WF) (equation 3) described by Shaw (1974, 1978, 1983)(See footnote at bottom of Table 4).

Measured or observed inputs were used for the DRAINMOD simulations wherever possible. These included most of the drainage system parameters, including periods of controlled drainage and subirrigation, hydraulic conductivity, maximum root depth, and Portsmouth soil properties reported by Gilliam et al., 1978). Daily maximum and minimum temperatures and daily rainfall were available from station records. Daily rainfall values were converted to hourly values by the disaggregation methods described by Robbins (1988). Prior to predicting yield, the inputs were calibrated by comparing 12 site-years of measured water table data to predicted values. The calibration procedure involved starting with all known or estimated inputs, running simulations for those fields and periods with water table data, then comparing predicted to observed water tables. This procedure was continued while varying other "estimated" inputs, primarily surface storage, upflux and root depth vs time relationship, until the combination of inputs providing the best water table fit were identified. The RMSE between the observed and simulated water table depths ranged from 12.1 to 21.2 cm/day. The RMSE and AABE of prediction for the pooled data was 15.8 and 11.3 cm/day, respectively. These results indicate that predicted values were in relatively good agreement with observed values. Detailed input values used in the simulations were reported by Evans (1991).

Statistical Procedures

The adequacy of the SDI models was tested by computing average error, average absolute error, root mean square error, and correlation between predicted and observed RY using standard statistical procedures (Evans, 1991). The fit of the predicted yields to the 1:1 line (perfect model) was compared by first determining the best fit linear regression line between predicted and observed yield using the method of least squares (SAS, 1985; Sendecor and Cochran, 1967). The intercept and slope of the best fit regression line was compared to those of the 1:1 line (intercept = 0, slope = 1) using the methods described by Ostle (1963). Finally, the fit of the data (predicted vs observed relative yield) was compared to the 1:1 line. The coefficient of determination, r^2, of this comparison was determined by dividing the best fit regression model sum of squares by the corrected total sum of squares. The corrected total sum of squares for this comparison was the best fit regression model sum of squares plus the error sum of squares $(RY_i - RY'_i)^2$ where RY_i is the relative yield predicted by the simulation model (not regression model) and RY'_i is the observed relative yield.

Predicted Corn Yield

Predicted relative yield components (wet, dry, plant delay), overall predicted relative yield and observed yields were reported in detail by Evans (1991). Space constraints prohibit their presentation here. Observed and predicted relative yield covered the full range of values from 0 to 100 percent, although a majority of values (about 80 percent) occurred in the upper half of the range (RY values between 50 and 100 percent). Over the total period, wet and dry stresses reduced average predicted RY about equally (about 15 percent each). In some years, predicted RY reduction was due entirely to wet or dry stress, but in most years, both wet and dry stresses contributed to the predicted RY reduction.

The AE, AABE, and RMSE for the pooled data are summarized in Table 5. The average error helps identify systematic errors in the prediction method. When the AE is greater than zero indicates that the model may be systematically overestimating observed values or underpredicting if the AE is less than zero. As seen in Table 5, the negative AE indicates yields were slightly underpredicted on average.

The AABE and RMSE provide an indication of the overall performance of the model in terms of the variation between predicted and observed values. The AABE indicates the average magnitude (sign ignored) of the error of each predicted value, with all errors weighted the same. If all errors are about the same magnitude, the AABE and RMSE will be about the same. The RMSE increases above the AABE as the number and magnitude of the poorer predictions increase. Thus, the RMSE provides a better indication of the range of errors.

Combining the results of the AABE and RMSE indicates that both methods had prediction errors of similar magnitude on average (AABE of 7.95 vs 8.89), but, prediction errors involving the severe-stress WF_d (Method 2) had a larger variation within individual observations (RMSE 9.89 vs 13.05).

	Corn SDI Models		
	Method 1 No WF	Method 2 WF = 1.5	Soybean SDI Model
Average Error	-1.35	-2.84	-0.44
Average Absolute Error	7.95	8.89	7.46
Root Mean Square Error	9.89	13.05	10.24
Correlation Coefficient r^2	0.808	0.710	0.559
Regression Line Intercept (Different from 0 alpha=0.05) no no yes	6.71	4.87	20.90
Slope	0.889	0.891	0.646
(Different from 1 alpha=0.05)	no	no	yes
1:1 Line forced through origin (Slope Different from 1 alpha=0.05)	no	yes	yes

Table 5. Goodness of fit evaluation of predicted to observed overall RY

The sensitivity of the prediction methods to year to year variation in soil-water stresses is best evaluated by comparing correlation between observed and predicted RY. These results are also summarized in Table 5. The intercept of the best fit regression lines for Methods 1 and 2 did not test significantly different from zero (0) at the 5 percent level of significance. The regression lines shown were then forced through the 0 intercept and the slope re-computed and tested against the slope of the 1:1 line (perfect model). The slope of Method 1 was not significantly different from 1 while the slope involving a severe-stress dry weight factor was significantly less than 1 indicating that RY was underpredicted when the severe-stress weight factor was used. Relative yield predicted by Method 1 is plotted against observed RY in Figure 3. Method 1 accounted for nearly 80 percent of the year to year variation in observed corn yield.

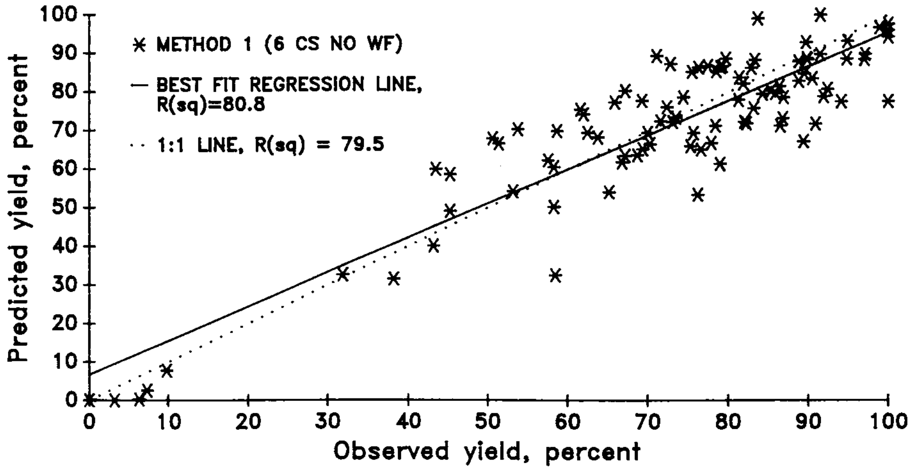

Figure 3. Observed and predicted corn relative yield, best fit regression line for pooled data from all North Carolina data (94 observations) and 1:1 line. (After Evans and Skaggs, 1992).

Predicted Soybean Yield

Soybean RY was predicted by equation 7 using equations 12, 13, and 14 to compute the individual yield components (wet, dry, and plant delay). The individual relative yield components, overall relative yield, and observed relative yield were summarized by Evans (1991).

Predicted and observed RY are plotted in Figure 4. Over 90 percent of the RY values (both predicted and observed) lie between 60 and 100 percent. Relative yields less than 50 percent were observed for only 6 cases. Average error, AABE and RMSE are summarized in Table 5. The AE was -0.44 percent, a slight underprediction.

The intercept of the best fit regression line between predicted and observed RY yield tested significantly greater than zero, Table 5. This could be due to the lack of data points at the lower end of the range. It could also be due to inadequacy of the prediction method. Predictions and trends were good for some years and completely reversed for others. Regardless, the adequacy of the model is best described in terms of correlation to the 1:1 line. The slope of the regression line forced through the intercept did not test significantly differently from 1, but the model explained only 47.9 percent of observed RY variation when compared to the 1:1 line.

The poor correlation between predicted and observed soybean RY may be due to several factors. Soybean can tolerate short term stress with little effect on yield. For example, if dry conditions exist during the pod set period, fewer pods are set. If conditions become more favorable during the subsequent pod fill stage, larger beans can be produced in each pod resulting in about the same yield as would have occurred if more pods had been set but filled with smaller beans. During stressful periods, some physiological processes can even be temporarily halted until more favorable conditions develop (Dunphy, not dated). The simple prediction methods evaluated herein are not capable of predicting these complex physiological recovery processes.

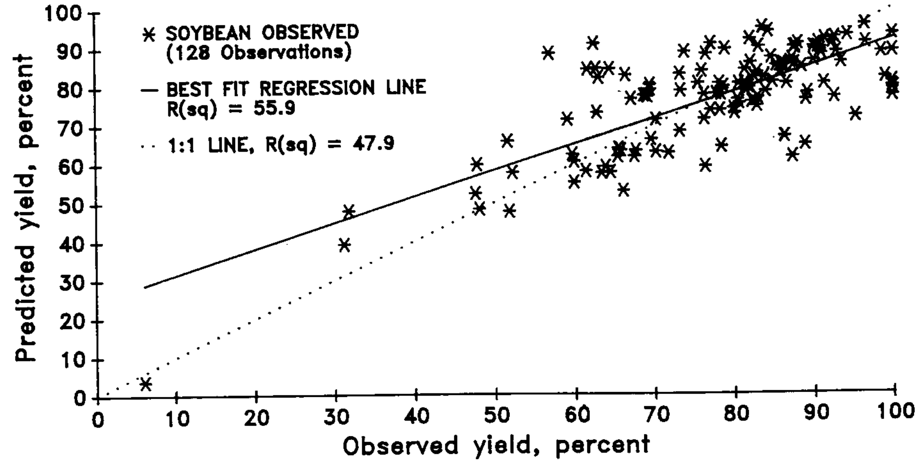

Figure 4. Observed and predicted soybean relative yield, best fit regression line for pooled data from North Carolina (128 observations) and 1:1 line. (After Evans and Skaggs, 1992.)

SUMMARY AND CONCLUSIONS

Crop susceptibility factors were presented for corn and soybean subjected to wet soil-water conditions (wet stresses). Using regression analysis, the crop susceptibility factors were used to develop Stress Day Index Models to predict corn and soybean yield response to high water table conditions.

Corn and soybean relative yield-stress day index models were tested with yields observed in field experiments conducted in eastern North Carolina. The yields were observed over a wide range of weather and soil-water conditions. Daily soil-water stresses resulting from the variable weather conditions were predicted using DRAINMOD. Yield reduction resulting from excessive and deficient soil-water stresses and planting delays were then predicted. All predicted yields were compared to observed yields with the goodness of fit evaluated using several statistical indicators.

The results presented showed that long-term average corn and soybean yields can be predicted with DRAINMOD using SDI models to predict the individual yield components (wet, dry and plant delay). The data tested suggest that severe-stress dry weight factors are not necessary to predict corn yield response to deficient soil-water stresses under traditionally high water table conditions such as exist in eastern North Carolina. Minor modifications to DRAINMOD would facilitate omission of the severe-stress criteria. This would reduce the required yield inputs because several 5-day CS values with the same value could be combined as one input. The methodology used to describe the deficient yield-SDI would then parallel the methods currently used to describe the wet yield-SDI relationship.

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DEVELOPMENT STUDIES WITH THE ADAPT WATER TABLE MANAGEMENT MODEL

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ABSTRACT. A subsurface water quality model, ADAPT (Agricultural Drainage and Pesticide Transport), has been developed by modifying GLEAMS and extending its use by adding drainage and sub-irrigation algorithms from DRAINMOD. Major processes of plant uptake, transformation and transport of nutrients and pesticides are included in the model. The hydrologic and pesticide components were evaluated with measured data from three water table management field facilities in Northern Ohio. Different strategies for modeling soil water redistribution were compared to determine their influence on the quantity and quality of surface and subsurface flows.

With limited calibration, the ADAPT model provided reasonable estimates of water table elevations, surface runoff, and subsurface drainage. Predicted estimates of pesticide concentration in the saturated zone and pesticide losses due to surface runoff and subsurface drainage were also considered acceptable. The model provides daily information but is only considered useful for estimating average hydrologic responses durinq periods of a week or longer.

An overview is presented of studies which are linking ADAPT to crop growth models, interfacing ADAPT with a GIS and river routing algorithms, and developing an expert system which: (a) will make the model more user friendly; (b) will use expert knowledge to modify soil hydraulic properties to account for changes in agricultural management practices; (c) will automatically conduct a sensitivity analysis; and (d) will use expert knowledge to provide quantitative and qualitative interpretations of the model outputs.

RESUME. *En modifiant le modèle GLEANS pour étendre son domaine d'application et en y ajoutant des algorithmes d'arrosage et de drainage tirés du modèle DRAINNOD, un nouveau modèle pour l'étude de la qualité des eaux souterraines, ADAPT, a été développé. Les processus de prélèvement, de transformation et de transport des éléments nutritifs y ont été incorporés. Des données expérimentales provenant de trois projets d'aménagement des eaux souterraines conduits dans le nord de l'Etat de Ohio ont été utilisées pour évaluer la composante hydrologique du modèle. Pour "modéliser" la redistribution de l'eau du sol, différentes stratégies ont été comparées en vue de déterminer leur influence sur la quantité et la qualité des écoulements de surface et du sous-sol. En dépit d'un calibrage limite, ADAPT a fourni des estimations satisfaisantes de la hauteur de la nappe d'eau, du ruissellement et de l'écoulement souterrain. Les estimations de la concentration de pesticide dans la zone saturée ainsi que de la perte de pesticide dans les eaux de ruissellement et de drainage sont aussi acceptables. Le modèle peut fournir des estimations journalières, mais est vraiment utile quant il s'agit d'évaluer des réponses hydrologiques s'étendant sur une période d'une semaine ou plus.*

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Une brève description est faite des études réalisées où on a combiné ADAPT a des modèles de croissance végétale, a des algorithmes de système d'information géographique, ainsi qu'a un système-expert. Ce dernier a rendu le modèle: (a) plus facile a utiliser; (b) capable d'expliquer les modifications des propriétés hydrauliques du sol en réponse a des changements de méthodes culturales; (cJ capable d'exécuter automatiquement des analyses de sensibilité; et (d) d'interpréter les résultats de modélisation.

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INTRODUCTION

Water table management practices to help maintain agricultural productivity and profitability without causing any degradation of water quality are required throughout the United States. In 1985, 44 million hectares of agricultural land benefitted from drainage improvements (USDA, 1987). Subsurface drainage has played a major role in increasing and maintaining high quality affordable food. However, its use is controversial as it has resulted in extensive drainage of swamps and wetlands. Subsurface drains influence surface and subsurface hydrologic systems. For example, in Northwestern Ohio, the largest area of interface occurs between the intensive row crop agriculture that has made the North Central Region the major producer of corn and soybeans in the U.S. and the immensely valuable freshwater of the Great Lakes. Also, while well water contamination by nitrates and pesticides in this region is currently limited (Baker et al., 1989), there is much concern that agricultural best management practices for reducing surface water contamination could aggravate ground-water contamination.

In North Carolina, controlled drainage has been established as a BMP in order to protect fish nursery areas and fragile aquatic ecosystems. Many studies have been made on positive and negative impacts of water table management practices and water table management field research is being conducted throughout the nation, much of it in the North Central Region, the Carolinas, and Louisiana. Researchers from these locations are coordinating their efforts in the NC-190 regional project, "The effect of water table management on productivity and water quality".

Computer advances have resulted in a proliferation of agricultural hydrologic models. In the United States, DRAINMOD (NCCI 1986) is the only water table management model which has seen widespread application. Research has been initiated to incorporate water quality capabilities into DRAINMOD, and two water quality versions have very recently been reported (Breve et al., 1992 and Kandil et al., 1992).

The CREAMS model (Knisel, 1980) was developed to evaluate non-point source pollution from field size areas. The migration of agricultural chemicals into the ground-water system necessitated the modification of CREAMS into the GLEAMS model (Leonard et al., 1987). To incorporate water table management practices, the ADAPT (Agricultural Drainage and Pesticide Transport) model was developed by extending GLEAMS to provide a comprehensive model to simulate the quantity and quality of flows associated with water table management systems (Chung et al., 1992a and 1992b). This paper provides an overview of ADAPT, and a summary of model evaluation studies and ongoing development research. Different strategies for modeling soil water redistribution are compared to determine their influence on the quantity and quality of surface and subsurface flows.

MODEL DESCRIPTION

The ADAPT model is a daily simulation model and has three components: hydrology, erosion, and chemical transport. The hydrology component of the ADAPT model includes snowmelt, surface runoff, macropore flow, evapotranspiration, infiltration, subsurface drainage, subirrigation, and deep seepage. The ADAPT model is PC based and written in FORTRAN language with modular programming techniques.

Hydrologic Component

The soil system is modelled from the soil surface down to an impermeable or restrictive layer. The top 10 mm is taken as the first layer, the rest of the effective rooting depth is equally divided into 6 layers, and the profile from the bottom of the root zone to the impeding layer is divided into two layers - making a total of 9 computational soil layers.

The snowmelt component is based on the theory presented by Anderson and Crawford (1964) and Viessman, Jr. et al. (1989). Snowmelt results from radiation, rainfall, conduction, convection, and condensation. Surface runoff is assumed to occur only if there is sufficient rainfall to fill the depression storage on the soil surface. Two options are provided for determining surface runoff depths based on Soil Conservation Service (SCS) curve numbers and antecedent soil moisture. The first option is taken from the GLEAMS model and the second option is the original SCS method as modified by Schmidt and Schulze (1987). An approach is included in ADAPT to account for surface sealing following intense rainfall on dry soils. Also, soil surface cracks due to dry soil condition are considered in the form of a runoff adjustment factor following Pathak et al. (1989). The model user can also specify the percentage of water available for infiltration which will be partitioned to macropore flow. All flow that occurs due to macropore flow is assumed to reach the water table within a one day period.

Potential ET can be calculated by the Ritchie method which is used in GLEAMS or the Dorenbos-Pruitt method (James, 1988). Evaporation and plant transpiration are determined separately as a function of the leaf area index (Knisel, 1980). Plant water uptake is determined for each soil layer with respect to root zone depth based on the approach in GLEAMS. The volume of water available for infiltration is rainfall and surface ponding minus runoff and macropore flow. A modified Green-Ampt equation (Mein and Larson, 1971) is used to calculate infiltration time. In the previously reported version of ADAPT (Chung et al., 1992a) the wetting front advances to the next layer when soil moisture content in a layer is at field capacity. When the wetting front reaches the water table, any additional infiltration will raise the water table height as pore spaces are filled from field capacity to saturation. If the total volume of available water does not infiltrate within 24 hours, the remainder carries over to the following day as surface ponding which is subject to evaporation and infiltration. Subsurface drainage and subirrigation algorithms are based on DRAINMOD (Skaggs, 1980). When the water table is at the soil surface, Kirkham's equation is used. Hooghoudt's steady state equation is used when the water table is below the soil surface. Both ADAPT and DRAINMOD use Darcy's equation to determine deep seepage through the impermeable layer but the modeling approaches are not identical. The new version of ADAPT accounts for upward movement of water from the water table and does not provide an upper limit (equal to field capacity) on the soil water content above the water table. The approach is based on the "drained to equilibrium" concept described by Skaggs et al. (NCCI, 1980) which is used in DRAINMOD.

Chemical Transport

Nutrient and pesticide transport in the system is generally the same as in the GLEAMS model. Each day, pesticide partitioning and degradation are calculated. The model estimates the concentration and the mass of pesticide transported by runoff, sediment, subsurface drainage, and deep seepage. It also calculates the mass of pesticide uptake by plants and loss by decomposition. Decomposition includes biodegradation and hydrolysis of a pesticide. The decomposition of the pesticide in the soil and on the plant leaf is assumed to follow first order kinetics. It is assumed that the pesticide concentrations of solid and solution phases in the soil profile are under equilibrium condition during the simulation period.
The processes of nutrients transformation in the ADAPT model were adopted from the GLEAMS nutrient model (Knisel et al., 1992). Two elements or nutrients, nitrogen and phosphorus, are included in the model. Common processes for both elements are mineralization from crop residue, soil organic matter and animal waste; immobilization to crop residue; plant uptake; nutrient partitioning between soil and solution phases; and nutrient transport by various mechanisms. On the other hand, the nitrogen has unique processes such as nitrogen fixation by legumes; denitrification; nitrogen in rainfall; ammonia volatization from animal waste; ammonification; and nitrification.

Nitrogen mineralization is considered as a first order ammonification process and a zero order nitrification process. Denitrification, the change of soil nitrate to nitrogen gases, occurs when soil water content exceeds field capacity. This is a first-order process with a rate constant as a function of organic carbon, water content and temperature. The processes of nitrogen transport include nitrogen in rainfall and fertilizer, in runoff and sediment, those in plant uptake, evaporation, subsurface drainage, and deep seepage flows. The processes of phosphorus transformations include mineralization and immobilization, while processes of phosphorus transport include phosphorus in runoff and sediment, plant uptake, evaporation, subsurface drainage, and deep seepage flows. Nutrient and pesticide concentrations discharging from a subsurface drain are very difficult to determine. The model provides an estimate of nutrient and pesticide solution concentrations in the layer at the top of the saturated zone. Concentrations in subsurface drainage are estimated as a depth weighted average of the concentrations in each of the layers between the top of the saturated zone and the impeding layer at the bottom of the modelled soil profile.

The vertical movement of pesticides and nutrients includes macropore flow, infiltration, and deep seepage. In macropore flow, water and chemicals move down to the water table within 24 hours. During infiltration, nutrients and pesticides are modeled as moving downward in sequence from one soil layer to the next. In each soil layer, nutrients and pesticides are added by infiltrating water from above, it equilibrates between the solid and solution phases, and then the solution moves downward to the next layer. This process is repeated until no further downward movement of water exists. Evaporating water transports pesticides in solution upward in the soil profile. The plant uptakes nutrients and pesticides in solution by transpiration in each layer depending on the root distribution in the soil. ADAPT can be used to model agrichemical injection in the subirrigation line. During subirrigation, it is assumed that agrichemicals move upwards along with the subirrigated water from the bottom layer to the water table layer.

MODEL INPUTS AND OUTPUT

To use the model, data input for weather, soil, crop, subirrigation/drainage system, and pesticide and nutrient parameters are required. Weather data include daily rainfall, air temperature, radiation, and wind speed. Soil data are soil texture, thickness of horizons, organic matter content, soil water characteristics, saturated hydraulic conductivity. In addition, surface storage depth; SCS curve number at antecedent soil water condition two; and relationships between water table depth, upward fluxes, and drained to equilibrium soil water contents are required. Crop data such as effective rooting depth and leaf area index as a function of growth stage are required. Subirrigation/drainage system input parameters include drain depth, spacing, diameter, outlet weir height, and depth to an impermeable layer.

Pesticide parameters include pesticide application date, amount, method, pesticide water solubility, foliar and soil half lives and the adsorption constant. Nutrient parameters include fertilizer and manure application date, amount, method; a nutrient partitioning coefficient which is calculated internally based on the clay content; crop data such as name, leguminous, potential yield, dry matter ratio, C/N ratio, N/P ratio, etc.; and nitrogen concentration in rainfall. Initial conditions are defined by parameters such as crop residue on the soil surface, base saturation, pH, calcium carbonate content, various nitrogen and phosphorous concentrations in the soil horizons.

Output data are daily, monthly, and annual estimates of surface runoff, subsurface drainage, combined surface runoff and subsurface drainage volumes, monthly rainfall, evapo-transpiration, deep seepage, and subirrigation volumes. Pesticide output includes concentration and mass in surface runoff, sediment, subsurface drainage, and deep seepage. It also includes pesticide concentrations in the soil layers and masses decomposed and uptaken by the plant. Nutrient output includes concentration and mass in surface runoff, sediment, subsurface drainage, and deep seepage. It also includes nutrient concentrations in the soil layers and masses uptaken by the plant.

EVALUATION AND DEVELOPMENT STUDIES

Study With Field Data From Castalia, Ohio

Complete details of this study are provided by Chung et al. (1992). The field capacity based version of the hydrologic component of ADAPT was evaluated with subsurface drainage field data from Castalia, Ohio. Studies conducted by Schwab et al. (1975) and Skaggs et al. (1981) provided most of the input data for this study. The experimental site was located at the North Central Branch, Ohio Agricultural Research and Development Center near Sandusky, Ohio. The site was nearly flat (0.2% slope) and the predominant soil type was a Toledo silty clay (poorly drained, fine, illitic, Mollic Haplaquept). Field plots were planted mostly in corn with conventional tillage. Field installations consisted of plots with surface drainage, subsurface tile drainage, and combinations of surface and subsurface drainage, each with four replications.

In general, runoff was slightly overpredicted and drainage underpredicted. However, considering no calibrated parameters were used in the model evaluation, the predicted combined values were in good agreements with the observations. A statistical analysis of observed versus predicted monthly runoff, drainage, and combined flows gave r-squared values of 0.87, 0.68, and 0.90 respectively. A sensitivity analysis was conducted with several of the input values and generally, observed values of runoff, drainage, and combined flows fell within the predicted ranges by using reasonable estimates for the tested model inputs.

Study With Field Data From Wooster, Ohio

The experimental site at Wooster is located at the Ohio Agricultural Research and Development Center at Wooster, Ohio, on a poorly drained Ravenna silt loam soil (fine, mixed, mesic Aeric Fragiaqualf). The site is nearly flat (less than 0.1% slope). The study was conducted with data for the period 1988-1991. Field plots were under conventional tillage and were planted in continuous soybeans in 1988 and 1989. Starting in 1990, a soybean-corn rotation was adopted with each crop in half the plot. Generally, the rate of water movement from the drain into the soil profile was too slow to satisfy ET requirements for corn and target water table elevations could not be maintained. Therefore, only the soybean plots were included in this study.

The drainage system consisted of 102 mm corrugated plastic tubing installed on 6.1 m centers and at a nominal depth of 0.9 m. In 1988 and 1989 plots with target water table depths of 0.25, 0.50, and 0.75 m were evaluated. In 1990 and 1991 these plots had the same target water table depths of 0.25 m.

Soil hydraulic properties used in the simulated study were primarily based on site specific measurements reported by Dorsey et al. (1990). The (SCS) Soils 5 data and a program developed by Baumer and Rice (1986) were used to determine drained volume and upflux relationships with water table depth. Observed water table elevation and water quality samples were obtained from perforated PVC tubes that extended 1.5 m into the profile.

Figure 1 shows a typical comparison between water table elevations that were determined with the two versions of the model.

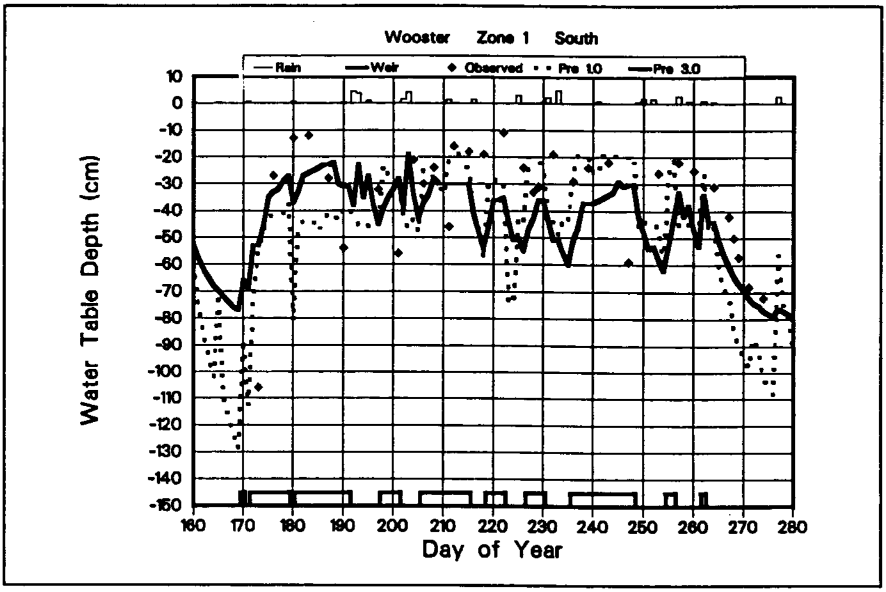

Figure 1.

To evaluate the performance of the old and new versions of the model, the period from day 170 to 270 was divided into 20 day blocks of time. A comparison was then made between the mean predicted and observed water table depths during each of these blocks of time. The comparison of observed water table depths results and those from the field capacity version of the model had an r2 of 0.63, a slope of 0.89 and a intercept of 0.11 m. The analysis with the upward flux version of ADAPT gave an r2 of 0.64, a slope of 0.90, and an intercept of 0.11. The observed and predicted mean water table depths were 0.65 m below the ground surface. It is probable that the predicted results are better than the statistical analysis indicates. At the research facility the system is switched from subirrigation to a drainage mode by: (a) stopping the water supply; (b) partially opening the drain outlets; (c) fully opening the drain; or (d) a combination of (a) and (b) or (c). In addition, the required water supply is estimated from experience. Records of supply and discharge rates are available but have not been fully analysed. In the ADAPT simulation, it was assumed that there was either subirrigtion with adequate water supply or unrestricted drainage.

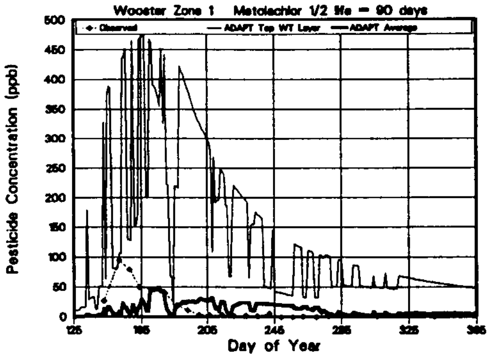

Figure 2A

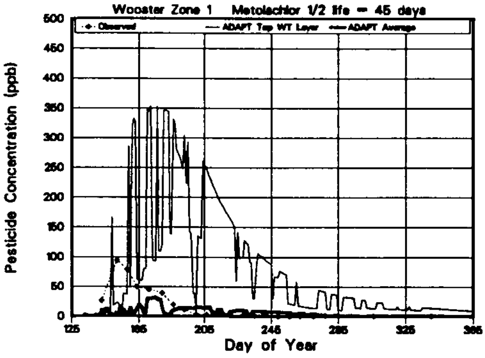

Figure 2B

Figure 2. Observed metolachlor concentration in perched water at Wooster compared with predicted values based on a soil half-life of 90 days and a half-life of 45 days.

Figures 2A and 2B show a comparison of predicted and observed metolachlor concentration in the perched water at Wooster, Zone 2. Figure 2A is based on commonly used estimates of 90 days for the soil half life for metolachlor. It can be seen in Figure 2B that reducing the half life to 45 days improves the timing of the predicted peak value and improves the prediction of the decay curve after the peak. Generally observed values fell between those predicted in the top layer, which is saturated, and estimates based on the depth weighted average concentration for all the saturated layers. Model predicted values are in acceptable agreement with the observed data considering order of magnitude variations are not uncommon at these low concentrations.

Study With Field Data From Hoytville, Ohio

The site is located at the North West Branch, Ohio Agricultural Research and Development Center, Hoytville, Ohio, on a Hoytville silty clay soil (poorly-drained, Mollic Ochraqualf). Details on the project, agricultural practices, soil properties, and observed flow and water quality data are given by Logan et al. (1993). Much of the soils input data was obtained from SCS Soils 5 data and generated by the Baumer and Rice (1986) computer program.

Table 2 shows a comparison of predicted and observed flows and pesticide losses by surface runoff and subsurface drainage at Hoytville. Mean observed values are for 8 plots - two replicates of no-till with corn, no-till with soybeans, conventional tillage with corn, and conventional tillage with soybeans. Each year atrazine and alachlor was applied to the corn plots; while metolachlor and metribuzine was applied to the soybean plots. All pesticides have been averaged over the 8 plots to account for carryover of herbicides from one year to the next. In general, atrazine was the only pesticide which was observed to exhibit significant carryover behavior. Results predicted by ADAPT in each year are the average of two simulations - a corn/soybean/corn/soybean rotation and a soybean/corn/soybean/corn rotation for the four year period.

Pesticide loss by subsurface drainage was less than 0.1% for all the pesticides applied indicating little pesticide transport to the depth of the subsurface drain system. In all years, both versions of the model provided reasonable estimates of surface runoff. In all years except 1987 most pesticide losses in surface runoff were greatly overpredicted. Subsurface drainage flows and pesticide losses were greatly overpredicted in 1987 but for the other three years both versions of the model provided reasonable estimates. The observed results reported by Logan et al. (1993) show no clear correlation of flows and pesticide losses with tillage practice. In addition, there was considerable variability in the hydrologic responses of each plot from one year to the next. It is anticipated that if knowledge of transient changes in soil properties were available the models would better predict the hydrologic responses. The results also indicate that improved knowledge is needed on how pesticides are incorporated into the near surface soil-plant-water system.

Surface Runoff (mm Depth and q/ha)						Subsurface Drainage (mm Depth and q/ha)			
		Predicted		Observed		Predicted		Observed	
Flow Depth and Pesticide	Applied Amount (kg/ha)	Ver 1	Ver 3	Range	(Mean)	Ver 1	Ver 3	Range	(Mean)
1987									
Flow Depth		22.9	10.3	2.1 -	30.7 (16.8)	78.3	34.2	0.5 -	14.9 (5.5)
Metolachlor	2.2	14.54	13.06	0.00 -	4.49 (0.75)	0.00	0.14	0.00 -	0.26 (0.04)
Metribuzin	0.6	4.68	4.06	0.00 -	1.30 (0.40)	0.00	0.41	0.00 -	0.25 (0.07)
Atrazine	2.2	8.28	13.73	0.08 -	1.38 (0.50)	0.72	1.05	0.02 -	10.1 (1.62)
Alachlor	2.2	5.32	7.88	0.00 -	0.89 (0.30)	0.16	0.66	0.00 -	0.16 (0.04)
1988									
Flow Depth		35.0	14.5	0.0 -	102.3	17.7	3.3	0.0 -	14.3 (3.1)
Metolachlor	4.5	3.19	0.79	0.02 -	(28.7)	0.03	0.01	0.00 -	0.37 (0.09
Metribuzin	0.6	0.03	0.01	0.00 -	23.77	0.00	0.00	0.00 -	0.04 (0.01)
Atrazine	2.5	0.33	0.09	0.02 -	(4.42)	0.01	0.00	0.00 -	0.08 (0.03)
Alachlor	2.2	0.00	0.00	0.00 -	4.03 (0.64) 14.70(2.95) 5.26 (1.43)	0.00	0.00	0.00 -	0.02 (0.00)
1989									
Flow Depth		58.7	62.7	17.4 -	83.4 (45.7)	186.0	116.9	80.1 -	334.6 (208.5)
Metolachlor	2.2	19.05	18.35	0.08 -	5.09 (1.83)	0.46	0.74	0.00 -	0.22 (0.08)
Metribuzin	0.6	1.68	1.57	0.00 -	29.7 (4.14)	0.01	0.04	0.00 -	0.07 (0.02)
Atrazine	2.2	12.63	36.94	0.06 -	3.50 (1.14)	0.19	0.25	0.01 -	1.08 (0.36)
Alachlor	2.8	6.46	16.68	0.40 -	2.03 (1.21)	0.02	0.08	0.00 -	0.09 (0.04)
1990									
Flow Depth		1610.	128.8	46.1 -	183.0 (111.0)	226.7	111.0	121.2 -	579.7 (141.4)
Metolachlor	2.2	7	17.51	0.16 -	7.08 (1.60)	0.30	4.57	0.12 -	7.48 (1.87)
Metribuzin	0.6	18.25	2.88	0.02 -	2.06 (0.44)	0.01	10.44	0.00 -	6.98 (1.40)
Atrazine	2.2	2.94	43.66	0.10 -	18.07	0.10	2.39	0.47 -	54.20 (10.87)
Alachlor	2.8	45.57 27.31	26.77	0.02 -	(3.79) 0.67 (0.21)	0.00	1.45	0.00 -	0.25 (0.09)

Table 1. Comparison of predicted and observed pesticide losses and flow rates at Hoytville.

Development studies

A comparison is being made of the Wooster results reported here which are based on soil measurements by Dorsey et al. (1989) and the extensive soils data base recently obtained by Hemminger (1993). Research is being conducted to include algorithms which account for macropore flow due to worm holes and organic matter. In addition, different strategies for determining the percentage of water from each layer that should be combined in drainage flow are being evaluated. With the Hoytville data, a statistical analysis is being made of monthly data and a study is being made of the sensitivity of predicted results to climatic inputs and uncertainties in the degradation parameters. An evaluation of the nutrient component of the model with data from both locations will be completed by the end of 1993.

Research has been initiated to link the model to the soybean crop development model SOYGRO (Jones et al., 1987) and the corn crop model CERES-MAIZE (Jones and Kiniry, 1986). The linked crop development version of ADAPT will be used in a study which will evaluate the usefulness of satellite thematic mapper data to provide calibration and model input information. This spatial-process model will be used in a funded study to determine agricultural impacts on Lake Erie.

In another study work has been initiated to develop a Basic Evaluation and Simulation Tool for Agricultural water Quality (BESTAQUA), an object-oriented expert system which will produce a complete, efficient, user-friendly, and practical system for use by consultants and farmers alike. BESTAQUA will be furnished with a visualization (multi-media) technique, including the use of an audio-video system. When fully developed, BESTAQUA will become an advisory system capable of suggesting ways of reducing the migration of agricultural chemicals into ground and surface water resources while still maintaining agricultural productivity and profitability.

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MANAGEMENT SUPPORT SYSTEM FOR CONJUNCTIVE IRRIGATION AND DRAINAGE

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ABSTRACT. This paper describes a computer-based Management Support System (MSS) for the design and management of conjunctive irrigation and drainage systems. This system is being developed at Colorado State University. The system will provide advanced technology to assist professionals in analyzing field-scale irrigation and drainage processes in semiarid and arid areas. The system models irrigation and drainage systems using several simulation modules. These modules are capable of considering the major processes of irrigation scheduling and application; precipitation; variably saturated and saturated flow and salinity transport; flow to subsurface drains; drainage effluent in collector drains, crop growth, evapotranspiration; and relative yield as affected by waterlogging, salinity and water deficits. The spatially-based output is displayed within the MSS to enable the user to interactively query the system and modify parameters and boundary conditions as needed for sensitivity analyses and for evaluating alternative design and management scenarios.

INTRODUCTION

Irrigated agriculture has been essential in this century to provide food and fiber for an expanding population. Production per unit area of irrigated land will become more important in the future. World population now stands at 5.3 billion and is projected to reach 10 billion by 2050. Most of the growth will take place in developing countries (IBRD, 1992). At the same time, the rate of expansion of irrigated land has decreased to less than 1% per year (FAO, 1979, 1989a, 1989b), and the productivity of many irrigation projects has been declining due to waterlogging, salinity and poor irrigation management practices.

This paper describes a computer-based Management Support System (MSS) that is being developed at Colorado State University (CSU). This MSS will be used for the design and management of conjunctive irrigation and drainage systems. The MSS can be used to improve the design and management of new irrigation projects and it can be used in the rehabilitation of existing projects.

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NEED FOR IMPROVED IRRIGATION DESIGN AND MANAGEMENT

Irrigation Development

For the year 1990, FAO (1990) indicated that the world's total irrigated land area was 235 million hectares. About two-thirds of this area was in Asia (FAO, 1979, 1989a). World Bank/UNDP (1990) estimated the "gross irrigated area" to be 253 million hectares. During the past four decades, development of irrigated agriculture has provided most of the increase in production necessary to meet population food demands. The World Bank estimates one-third of the total crop production came from irrigated land, while irrigated land makes up only 15 percent of the total arable land. The rate of expansion of irrigated land reached a peak of 2.3 percent per year from 1972 to 1975. Since this time the rate of expansion has declined and is now less than 1 percent per year (FAO, 1990). The declining rate of expansion is due in part to higher costs and lower performance than expected.

Waterlogging, Soil Salinity and Drainage

Decreased production on many irrigated projects is caused by waterlogging followed by soil salinization. Waterlogging and salinity can be prevented by better water control methods and by assuring that all irrigation projects have adequate drainage. In the mid-1980s, the United Nations predicted that by 1990, 52 Mha of irrigated land would require drainage to control soil salinity (Oosterbaan, 1988).

Integrating Irrigation and Drainage System Design

Historically, most irrigation and drainage systems were designed separately and the responsibility for the management of irrigation systems has generally been assigned to different agencies than those handling drainage systems. The optimal use of irrigated agricultural lands requires irrigation and drainage systems to be designed, constructed and managed as an integrated unit. To fully understand and predict long-term performance and to account for component interaction, modeling and simulation are needed. A combined system can be very complex. For example, irrigation practices have direct effects on the water table and drain spacing is dependent on excess water applied in addition to rainfall. Therefore, the costs and benefits of irrigation and drainage systems should be mutually considered for good management.

Modeling Irrigation and Drainage Systems

Many of the variables affecting irrigation and drainage systems are stochastic in nature. Irrigation scheduling is based on evapotranspiration (ET), crop growth stage and available soil water. The stochastic nature of meteorological variables can be simulated using a weather generator. Generated meteorological time series can be used as input to the scheduling model. The resulting stochastic schedules create uncertainty in the system behavior. Similarly, system boundary conditions, soil flow and formation properties (hydraulic conductivity, pressure-saturation characteristics, etc.), irrigation application efficiency and other parameters can be modeled as cross-correlated, spatial-temporal random fields.

Modeling and computer based simulation can be effective tools in considering the stochastic nature of temporal data, integrating irrigation and drainage system design and assisting managers in solving waterlogging and soil salinity problems in irrigation development.

GENERAL DESCRIPTION OF THE MODEL DEVELOPMENT

The Colorado State University Irrigation and Drainage Model (CSUID) is being developed with three main functions; editing input, using the numerical model, and analyzing the output. A graphical user interface (GUI) helps the user with these many functions. These modules are capable of considering the major processes of irrigation scheduling and application; precipitation; variably saturated and saturated flow and salinity transport; flow to subsurface drains; drainage effluent in collector drains, crop growth, evapotranspiration; and relative yield as affected by waterlogging, salinity and water deficits.

The System

The system requires historical meteorological time series data for the irrigation scheduling module. These data are used to create a set of daily reference crop ET values using one of the following equations: Penman-Monteith, FAO Penman, or Jensen-Haise (Jensen, et al. 1990). Reference crop ET values are multiplied by experimentally derived crop coefficients to provide actual ET estimates for each crop.

When modeling irrigation and drainage as a conjunctive system, the inputs to CSUID are stochastic in nature. Irrigation scheduling is based on estimated ET and rainfall which is a function of meteorological crop and soil variables including crop growth stage and soil water. The stochastic nature of the meteorological time series can be simulated using a weather generation model or input as measured data. In this work, a model called WGEN (Richardson, 1984) is used to generate the stochastic time series of meteorological data. Generated meteorological time series are then used as input to an irrigation scheduling component of the MSS.

CSUID allows the user to determine drainage requirements initially using a two-dimensional vertical plane analytical model (Dumm, 1964). This two-dimensional model allows the user to initially screen alternative irrigation schedules and drain spacings. This portion of the MSS contains an ET, crop growth, an upward flow component, and the ability to estimate relative yield as affected by waterlogging, salinity and soil water deficits. The user can generate a number of synthetic time series and model different irrigation practices on a two-dimensional plane. After evaluating the results of these scenarios, the user can access a numerical model and analyze the results in the form of graphical output files using the MSS.

The Numerical Model

The numerical model allows the user to study the effects of spatial variations in input data. A quasi-three dimensional model is used as the basis for computing spatial and temporal distributions of soil water and salinity as affected by field-scale practices of irrigation and drainage.

The model solves the depth-averaged Boussinessq equation for areal flow in the saturated zone below the water table and the Richard's equation for one-dimensional vertical flow in the variably saturated zone above the water table. The mixing cell concept is used to predict advection-dominated salinity transport. Solutions are obtained using finite difference approximations of the equations at discrete grid points in the domain. In addition to calculating salinity and water distributions, the model predicts depth to the water table, upward flux from the water table, leaching efficiency, volume and salinity of drainage effluent collected, and relative crop yield. The control variables describing irrigation and drainage alternatives are the amount, timing, and depth of the salinity of irrigation water applied, the spacing and slope of lateral subsurface drains. The model explicitly considers variability due to the diverse soil and crop properties and irrigation practices on multiple fields in an area.

The model is a link model which separates the saturated and variably saturated component of the system, each of these components can be simplified due to their generic characteristics. The fundamental difference that exists between saturated and variably saturated flow is exploited to obtain a computationally efficient solution algorithm instead of smoothing their differences with a single and less flexible generalized equation.

The system can be subdivided into two distinctly different zones namely the variably saturated zone and the fully saturated zone. The analysis, however, is not totally inclusive. Rather, it is said to be linked or coupled because recharge and storage properties of one zone influence the behavior of the other zone. In variably saturated zone, the lateral flow can be considered to be negligibly small when compared to the vertical flow component. This allows analysis of the variably saturated zone using the Richard's equation for one-dimensional vertical flow. On the other hand, using the Dupuit assumptions, the flow in the fully saturated condition is considered to be strictly horizontal and the model solves the depth-averaged Boussinessq equation. This approach has been used by several researchers including Pikul et al. (1974), Kashkuli (1981), Mankarious (1986), Jalut (1989) and Farida (1991).

With the above approach, the movement of salt in the two zones is modeled separately. Salt movement is considered here an a-posteriori event and the bulk velocities, assumed to be the main agents of salt movement, are known beforehand from the solution of the flow equations. It follows, that the salt movement in the variably saturated zone be analyzed in one dimension along the vertical direction and in two dimensions along the horizontal plane of flow in the fully saturated zone.

Auxiliary functions

The behavior of hydraulic conductivity and saturation with respect to pressure head can be defined by empirically-based nonlinear functions. The more established relationships are those of Brooks and Corey (1964), Haverkamp et al. (1977) and van Genuchten (1980). CSUID includes these three types of relationships including the extended van-Genuchten relationship that has been suggested by Paniconi et al. (1991).

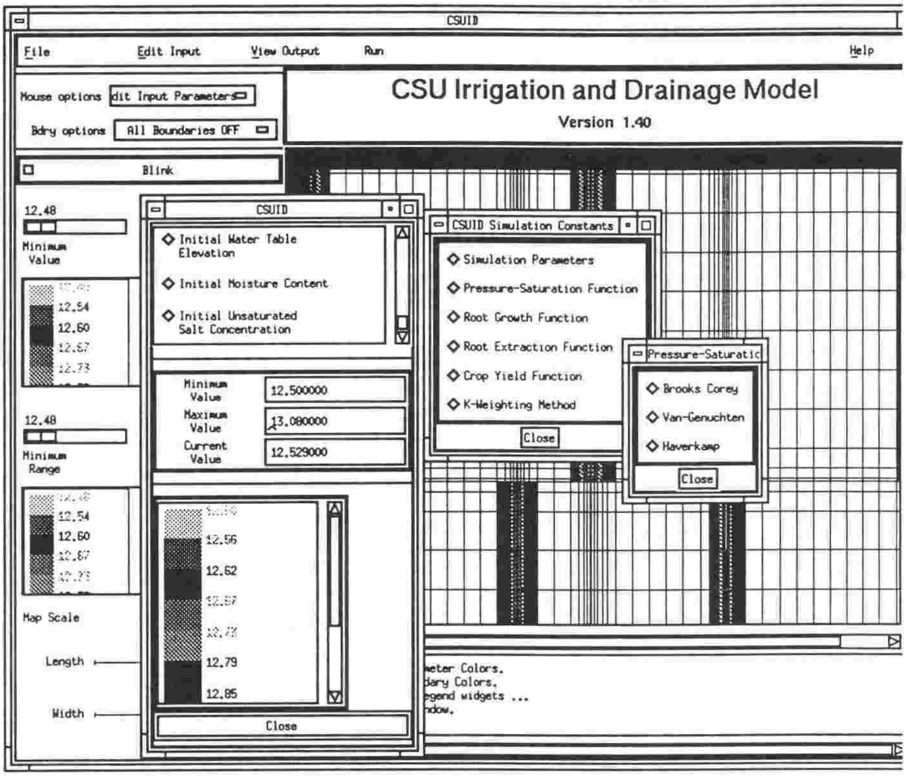
Different plant water uptake functions are also used. Table 1 lists these functions. It can be noted that not all functions include the influence of salinity. The interblock hydraulic conductivities for the variably saturated zone use a block centered grid scheme that can be computed in different ways. The saturated zone uses the harmonic method to compute interblock hydraulic conductivity. Table 1 lists the available methods.

Plant Water Uptake Functions	Interblock Hydraulic Conductivity Methods for the variably saturated zone
van Genuchten (1987)	Upstream Weighting
Molz & Remson (1970)	Arithmetic Mean
Hillel et al. (1976)	Harmonic Mean
Lappala et al. (1987)	Geometric Mean
Feddes et al. (1974)	
Gardner (1964)	
Whisler et al. (1968)	
Herkelrath et al. (1977)	

Table 1. Choices for Functions and Methods

CSUID GRAPHICAL USER INTERFACE

CSUID was written to run on a Sun UNIX workstation. The GUI was developed using the "C" programming language combined with "Motif" and "X Intrinsic Libraries" for the graphics. A commercial graphical interface builder tool called "TeleUSE" was used for the interface development. The GUI is based on a mouse-driven approach with menus and pop-up windows. The user-friendly interface frees users from the normal tedium associated with large amounts of data input, the programing of a numerical model and the analysis of numerical output in the form of large output files. An example screen for editing input is shown in Figure 1.



Mouse options: dit Input Parameters

Bdry options: All Boundaries OFF

Minimum Value: 12.500000

Maximum Value: 13.080000

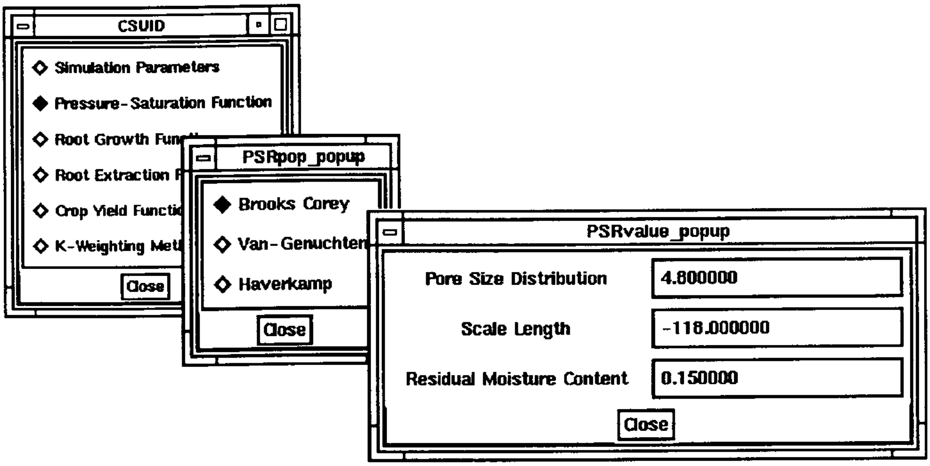
Current Value: 12.529000

Figure 1. Example Screen for Editing Input

The screen displayed in Figure 2 is divided into two major areas with the menu bar at the top of the screen and the options displayed on the left hand side of the screen. The major components of the top menu are the Edit Input, and the View Output sections. Each of these components are explained in more detail below.

Edit Input

"Edit Input" allows for the selection of parameters, boundaries, the irrigation schedules and the time series for input files. The parameters include overall constant values like the grid size as well as choices for types of numerical analysis options like the pressure saturation functions, root growth functions, root extraction functions, crop yield functions and the interblock hydraulic conductivities. When one of these functions needs additional information a pop-up window will be displayed (Figure 2). The parameters have a visual display with options for setting the maximum and minimum values, along with individual value editing on the grid. Some of the different types of parameters that can be displayed are variably saturated physical, saturated physical, irrigation, crops, salts, and global parameters (Figure 2 has the initial water table elevation displayed). The system is laid out in a modular fashion to allow the addition of more components as they become available. One of the major strengths of CSUID is the ability to allow the user to explore the differences between different representation of the same concept (Figure 3), the user can use the Brooks-Corey, Van Genuchen, or Haverkamp Pressure-Saturation functions by selecting the appropriate option and entering the specific data required for each option. The user is referred to the CSUID users manual for more detailed information on the options of this system (IDS, 1993).



◇ Simulation Parameters
◆ Pressure-Saturation Function
◇ Root Growth Fun
◇ Root Extraction
◇ Crop Yield Functi
◇ K-Weighting Met

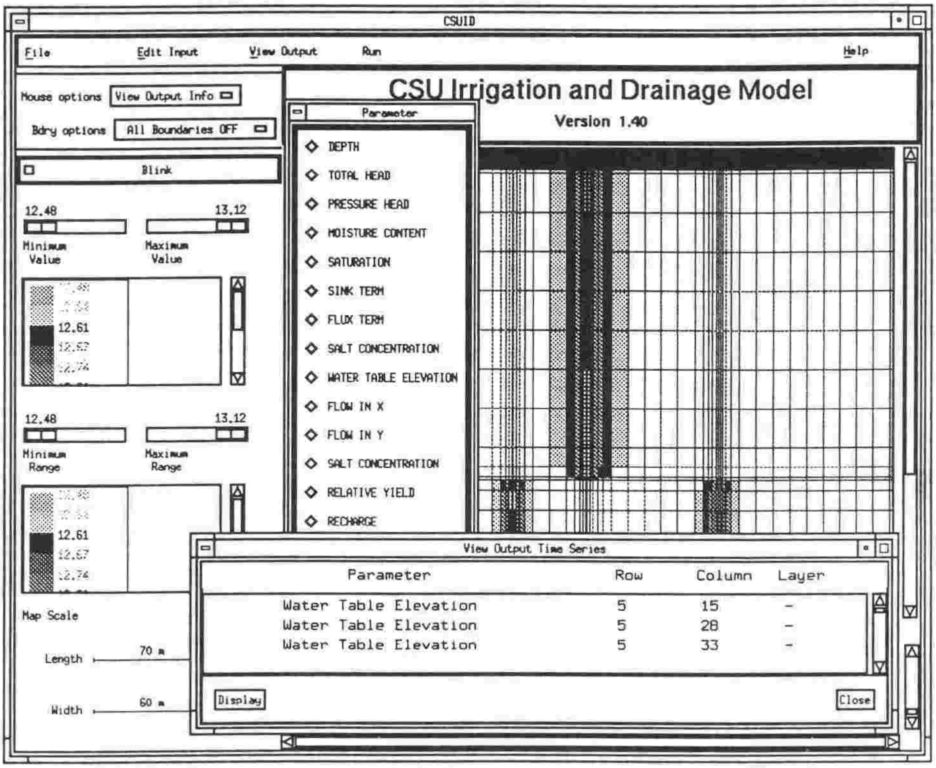
◆ Brooks Corey
◇ Van-Genuchten
◇ Haverkamp

Pore Size Distribution 4.800000
Scale Length -118.000000
Residual Moisture Content 0.150000

Figure 2. Additional Information Windows

View Output

"View Output" allows for analyzing output files made by the numerical model. The numerical model generates files that contain information for multiple layers in the variably saturated zone and a mixed-cell concept in the saturated zone. The interface provides the user with a list of layers (variably saturated zone) or a single layer in the saturated zone. Since the process that is being analyzed contains spatial as well as temporal variations, the user is provided with the ability to display an X-Y graph of data at any point in either space or time in the system. In Figure 3, the interface for the View Output Time Series is shown with Water Table Elevation data for several locations. At the present time, the system displays horizontal sections of the area. In a new version of the system under development, the user will also have the ability to display cross-sectional displays of the area.



Mouse options: View Output Info

Bdry options: All Boundaries OFF

Map Scale

Length 70 m

Width 60 m

Parameter	Row	Column	Layer
Water Table Elevation	5	15	-
Water Table Elevation	5	28	-
Water Table Elevation	5	33	-

Figure 3. Example of Viewing Output

CONCLUSIONS

The MSS being developed at Colorado State University allows analysts to manipulate the large amount of information required to design conjunctive irrigation and drainage systems and analyze and develop scenarios for redesigning an existing system. This MSS allows the user to visualize the spatial distribution of the input and output from the model, significantly reducing the amount of effort involved in the creation and/or debugging of a input data set. Improved understanding of the output is possible using the GUI. The system is expected to be used to perform research on many of the unanswered question regarding the characterization, design and management of irrigation and drainage in regions affected by saline, shallow ground-water tables.

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DRAINMOD-S: WATER MANAGEMENT MODEL FOR IRRIGATED ARID LANDS, CROP YIELD AND APPLICATIONS

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ABSTRACT. The primary objective of an agriculture water management system is to provide crop needs to sustain high yields. Another objective of equal or greater importance in some regions is to reduce agriculture impacts on surface and groundwater quality. Kandil, et al. 1992 modified the water management model DRAINMOD to predict soil salinity as affected by irrigation water quality and drainage system design. The objectives of this study are to incorporate an algorithm to quantify the effects of stresses due to soil salinity on crop yields and to demonstrate the applications of the model. DRAINMOD-S, is capable of predicting the long-term effects of different irrigation and drainage practices on crop yields. The overall crop function in the model includes the effects of stresses caused by excessive soil water conditions (waterlogging), soil water-deficits, salinity, and planting delays. Three irrigation strategies and six drain spacings were considered for all crops. In the first irrigation strategy, the irrigation amounts were equal to evapotranspiration requirements by the crops, with the addition of a 10 cm depth of water for leaching applied during each growing season. In the second strategy, the leaching depth (10 cm) was applied before the growing season. In the third strategy, a leaching depth of 15 cm was applied before the growing season for each crop. Another strategy (4th) with more leaching was considered for bean which is the crop most sensitive to salinity. In the fourth strategy, the irrigation was set at 14 days intervals were used instead of 7 and leaching irrigations were applied: 15 cm before the growing season and 10 cm at the middle of the growing season for bean. The objective function for these simulations was crop yield. Soil water conditions and soil salinity were continuously simulated for a crop rotation of bean, cotton, maize, soybean, and wheat over a 19 year period. Yields of individual crops were predicted for each growing season. Results showed that the third irrigation strategy resulted in the highest yields for cotton, maize, soybean and wheat. Highest yields for bean were obtained by the fourth irrigation strategy. Results are also presented on the effects of drain depth and spacing on yields. DRAINMOD-S is written in Fortran and requires a PC with math-coprocessor. It was concluded that DRAINMOD-S is a useful tool for design and evaluation of irrigation and drainage systems in irrigated arid lands.

RESUME. *DRAINMOD-S.: un modèle pour la gestion de l'eau, pour irriguer les régions arides et améliorer la productivité végétale. Le premier but d'un système de gestion de l'eau est de déterminer les besoins de la végétation pour avoir une meilleure production; un autre but, qui est plus important dans certaines régions, est de réduire l'impact de l'agriculture sur la surface du sol, et de maîtriser la qualité de l'eau. Kandil et al. 1992 ont modifié le modèle de gestion de l' eau (DRAINMOD) pour prédire l'influence de l'irrigation et du drainage sur la qualité de l'eau et la salinité des sols. Les buts de cette étude sont de trouver l'influence de la salinité du sol sur la production végétale et de présenter les applications possibles du modéle.*

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DRAINMOD-S a la capacité de prédire l'influence de différents modes d'irrigation et de drainage sur la production végétale sur de longues périodes. La fonction de production du modèle inclut les effets de stress hydrique du à un excès d'eau, de déficit hydrique, de salinité et de retard au semis. Trois stratégies d'irrigation et six modes de drainage sont utilisées pour l'ensemble des végétaux. Dans la première stratégie d'irrigation, l'apport d'eau était égale à la demande du végétal, avec une dose supplémentaire de 10cm appliquée à chaque stade de la croissance pour lessivage. Dans la deuxième stratégie le lessivage a été utilisée avant la saison de croissance. Dans la troisième stratégie, un lessivage de 15 cm a été utilisée avant la saison de croissance pour chaque culture. Une quatrième stratégie a été utilisée pour la culture de féve, plus sensible à la salinité. Dans cette dernière stratégie, l'irrigation a été appliqué à 14 jours d'intervalle au lieu des 7 jours; une dose de lessivage de 15 cm a été appliquée avant la saison de croissance puis une dose de 10 cm au milieu de la saison de croissance. La fonction objectif du modèle pour ces simulations était le rendement de la culture. Les états hydriques et la salinité du sol ont été simulés pour la rotation des végétaux, féve, coton, blé, graines de soja et maïs sur une période de 19 années. La production de chaque culture a été prédite pour chaque saison de croissance. Les résultats ont démontré que la troisième stratégie d'irrigation a entraîné de meilleurs rendements pour le coton, le maîs le soja et le blé. Les rendements les plus élevés pour la féve ont été obtenus avec la quatrième stratégie d'irrigation. DRAINMOD-S a été écrit en Fortran et est exécutable sur PC équipé d'un coprocesseur arithmétique. En conclusion, DRAINMOD-S est un outil efficace pour le dimensionnement, l'évaluation des besoins en irrigation et drainage des terres arides irrigables.

INTRODUCTION

Waterlogging problems in arid and semiarid regions are usually associated with high soil salinity problems. Salinity build-up in the soil can have an adverse effect on crop yield because of a large number of factors. The processes involved are complicated, and are interrelated with such factors as crop species, soil properties, salinity and chemistry of irrigation water, and subsurface drainage. The development of a crop and its subsequent yield are highly dependent on the quantity and quality of water available to the crop in the root zone.

Kandil et al., 1992 describes modifications to DRAINMOD to include the effect of irrigation water quality, the timing and amount of application, and drainage system design on soil salinity and drainage water quality. The water management model DRAINMOD was modified to predict salt concentrations in the soil profile and drainage water. The new model is called DRAINMOD-S. It includes an explicit solution of the advective dispersive equation to predict solute transport. The solute transport part of DRAINMOD-S was tested against a more complex numerical model. The reliability of DRAINMOD-S for artificially drained arid soils was also evaluated using data collected in field experiments Egypt. The input data requirements for the model include several drainage system parameters (such as drain depth, drain spacing, and radius of the drain), soil parameters (soil water characteristics, hydraulic conductivity, depth to impervious layer, and initial soil and ground water salinities, and weather and management variables (rainfall, evapotranspiration, quantity, quality of and timing of irrigation water).

The objectives of this study were (1) to incorporate into DRAINMOD-S an algorithm to predict the effect of soil salinity on crop yield; and (2) to demonstrate the capabilities of the model by conducting long term simulations to evaluate effects of different irrigation strategies and drainage designs on crop yields for a location in the Nile Delta.

CROP YIELD MODELING

Excessive soil wetness caused by high water table, waterlogging or flooding is stressful to most crops. The water management simulation model, DRAINMOD, (Skaggs, 1978) has been used to design and manage drainage and subirrigation system in humid regions. Skaggs et al. (1982) developed an approximate method based on the stress-day index (SDI) concept (Hiler, 1969) to predict corn yield response to stresses caused by excessive soil water conditions. The following algorithm may be used for corn:

$$RY_W = 100 - 0.71\ SDI_W \qquad (1)$$

where coefficients of the equation, 100 and 0.71 are data inputs for corn only and SDI_W is the stress-day index for excessively wet conditions, which may be expressed as:

$$SDI_W = \sum_{j=1}^{N} CS_{wj}\ SDW_j \qquad (2)$$

where N is the number of days in the growing season, CS_{Wj} is the crop susceptibility factor for excessive soil water conditions for day j, and SDW_j is the stress day factor for Day j. The stress-day factor is taken to be the same as the daily value of SEW and may be expressed as follows

$$SEW_{30} = \sum_{j=1}^{n} (30 - X_j) \qquad (3)$$

where X_j is the water table below the soil surface on day j and n is the number days in the period being considered. Only positive values of $(30 - X_j)$ are considered; the units for SDI_W are centimeter-days.

A yield response function to deficient soil water conditions (Shaw, 1978) was also included in the DRAINMOD:

$$YR_d = 100 - 1.22\ SDI_d \qquad (4)$$

where SDI_d is the stress-day index for drought conditions. The coefficients in the equation, (100, and 1.22 for corn in this case) are data inputs which will be different for other crops. The SDI_d is the stress-day index for drought conditions and is defined on a cumulative basis as

$$SDI_d = \sum_{j=1}^{N} SD_{d_j} \times CS_{d_j} \qquad (5)$$

where SD_{dj} and CS_{dj} are the stress-day and crop susceptibility factors, respectively for growth period j, and N is the number of periods in the growing season. The stress-day factor is defined as

$$SD_{d_j} = \sum_{k=1}^{n_j} \left(1.0 - \frac{AET_k}{PET_k} \right) \qquad (6)$$

where AET_k and PET_k are the actual and potential daily ET, respectively, and n_j is the number days in the jth growing period. Crop susceptibility factors are given in the DRAINMOD user manual. Another function is also used in DRAINMOD, to calculate the drop in yield resulting from delayed planting. This relationship was studied by Semour et al. (1992), who presented input data values for corn for several locations in the U.S.

The response of crop yield to soil salinity is traditionally described for a given crop by plotting two linear lines, one a tolerance plateau at a relative yield of 100% up to a salinity threshold, and the other a concentration-dependent line whose slope indicates the yield reduction per unit increase in the soil salinity (Maas and Hoffman, 1979). For soil salinity exceeding the threshold of any given crop, relative yield can be estimated with the following equation:

$$RY_s = 100 - b(SAL_e - a) \qquad (7)$$

where a is the salinity threshold expressed in mg/l; b is slope expressed in % per mg/l; and SAL_e is the mean salinity of the saturated-soil extract in the root zone. The thresholds and slopes of 69 crops were given by Maas and Hoffman, 1979. Most of the data were obtained from crops grown under conditions that simulated recommended cultural and management practices for commercial production. The data apply only where crops are exposed to fairly uniform salinities from the late seedling stage to maturity.

In this work, an algorithm (Equation 260) was added to DRAINMOD-S to predict the effect of salinity in the root zone on crop yield. Thus, the general crop response model for DRAINMOD-S can be represented as follows:

$$RY = RY_w \times RY_d \times RY_p \times RY_s \qquad (8)$$

where RY is the overall relative yield for a given year, RY_w is the relative yield that would be obtained if only wet or excessive soil water stresses occurred, RY_d is the relative yield that would be obtained if only drought stresses occurred, RY_s is the relative yield that would be obtained if the only stress is due to soil salinity, and RY_p is the relative yield resulting from planting delays. To compare predicted yields to field measured yields, relative yield may be expressed as: $RY = Y/Y_o$ where Y is the measured or observed yield for a given year and Y_o is the long-term average yield that would result from a combination of abundant irrigation, good drainage, favorable root zone salinity and good trafficability so that planting and other field operation can be done on time (Evans, et al. 1991).

PROCEDURES

DRAINMOD-S was validated for conditions at the Zankalon Pilot area in the Nile Delta (Kandil et al., 1992). In this paper, the model was used to compare the performance of several drainage and irrigation strategies for the same location. A rotation consisting of five crops was considered. The crops were Bean, Cotton, Maize, Soybean, and Wheat. This represents typical crop rotation in Egypt's Nile Delta of Egypt. The soils and climatic data for Zankalon presented by Kandil et al. (1992) were assumed in this study.

Soil and Drainage System Parameters

The soil at Zankalon is primary silty clay and clay with lateral saturated hydraulic conductivity of approximately 0.5 cm/hr. Soil water characteristics, unsaturated hydraulic conductivity-pressure head relationship, Green-Ampt infiltration coefficients, volume drained-water table relationship, and maximum upward flux-water table relationship were taken as in Kandil et al. 1992. A schematic diagram of the profile considered in this study is shown in Figure 1. The drainage parameters used in the simulations are given in 261. Simulations were performed for drain spacings of 15, 20, 30, 40, 50, and 100 m at a drain depth of 1.2 m. Additional simulation were conducted for drain depths of 1.0 and 1.4 m.

Parameter	
Drain Spacing (L), (m)	15,20,30,40,50,100
Drain Diameter (d),(mm)	100
Effective Radius r_e (cm)	1.5
Drain Depth (a), (m)	1.0,1.2,1.4
Distance for Drain to Restrictive Layer (b), (m)	0.4
Drainage Coefficient (mm/d)	25.0

Table 1. Summary of the drainage input parameters used in the simulations

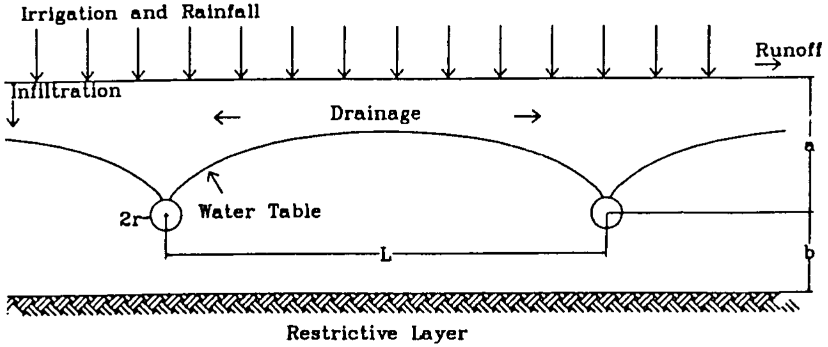

Figure 1. Schematic diagram of water management system with subsurface drains

Crop Data

The order of crops grown in the rotation was bean, maize, wheat, cotton, and then soybean. The simulations were performed for 19 years of a climatological data collected from meteorological station located 25 Km northeast of the Zankalon Pilot Area. The salinity of the irrigation water was taken as 400 mg/l. The initial soil salinity was assumed to be 1500 mg/l (Saturation Extract). The change in the effective root depth with time was estimated using Crop Growth Stage Coefficients (K_c) as discussed in Kandil et al. 1992. The maximum effective rooting depth was assumed to be 40, 80, 35, 75, 45 cm for bean, cotton, maize, soybean, and wheat respectively.

Crop Yield Predictions

The number of growing seasons during the simulation period (19 years) were 7 for bean, 13 for cotton, 7 for maize, 6 for soybean and 7 for wheat. The yield for each crop was predicted in DRAINMOD-S using Equation 8. The individual yield components in Equation 8 were calculated with Equation 1 to 7. Input parameters for Equations 1-7 that relate yield to stresses due to soil salinity, excessive soil water and deficient soil water conditions along with stress-day factors were taken from Evans et al., 1991 and Mass and Hoffman, 1977. It was assumed that trafficability would not be limiting under arid conditions, as irrigation could be scheduled such that crops could be planted on time. Thus, the factor RY_p in Equation 8 was set to 1.0. Input parameter for cotton and wheat were taken equal to the ones for maize. Parameters for bean were set equal to the soybean factors. Stress day index factors were adjusted to account for the differences in length of growing seasons and stages.

Irrigation

Irrigation water was assumed to be applied by basin irrigation with each basin surface leveled to eliminate cross slope and leave little or no slope in the direction of irrigation. Each basin was surrounded with dikes to prevent runoff. Three irrigation strategies were evaluated for all crops. In the first strategy, the irrigation amounts were equal to evapotranspiration requirements by the crops, with the addition of a 10 cm depth of water for leaching applied during each growing season. In the second strategy, the leaching depth (10 cm) was applied before the growing season. In the third strategy, a leaching depth of 15 cm was applied before the growing season for each crop. Another strategy (4th) with more leaching was considered for bean, which is the crop most sensitive to salinity (Mass and Hoffman, 1977). In the fourth strategy, the irrigation was set at 14 days intervals instead of 7 and two leaching irrigations were applied: 15 cm before the growing season and 10 cm at the middle of the growing season for bean.

RESULTS AND DISCUSSION

Predicted relative yields for each crop were averaged over the respective number of growing seasons in the 19 years period of simulation. The averaged predicted relative yields (RY) for each crop are plotted as a function of drain spacing in Figure 2 for the first irrigation strategy. Theses yield results, reflect the effects of drainage rates on soil water and salinity conditions. Yield results for cotton were not responsive to drainage because of its high tolerance to soil salinity (Mass and Hoffman, 1977). On the other hand, the yield results for bean and maize were dramatically reduced below the optimum at all spacings because of their high sensitivity to salinity. Soybean and wheat show an intermediate response to drainage for this irrigation strategy.

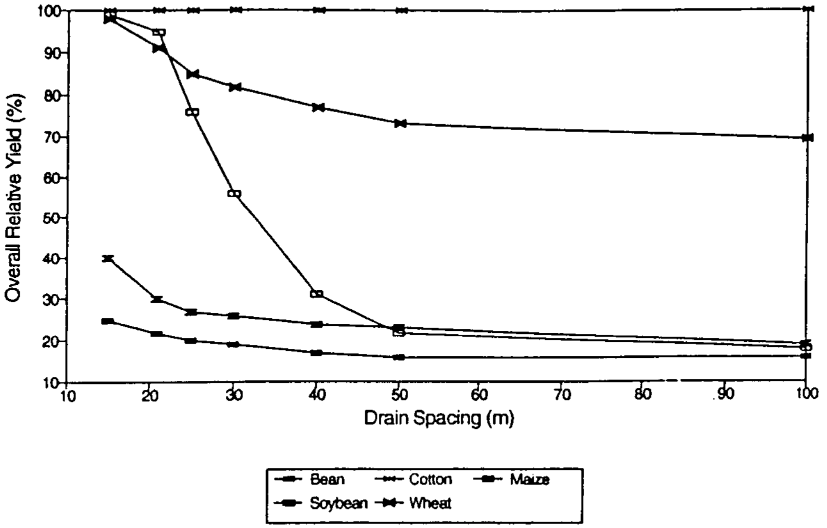

Figure 2. The averaged overall predicted relative yields (RY) for all crops as a function of drain spacing.

Bean

Average predicted relative yield components (RY_w, RY_d, RY_s, and RY) for the seven bean crops in the 19 year simulation period are given as a function of drain spacing in Table 2 and Figure 3 for all irrigation strategies. Results for the first irrigation strategy indicate that soil water conditions in the root zone were favorable with only a 3% drop in yield due to deficit water conditions (RY_d). Stresses due to excessive soil water did not limit yields (i.e. RY_w=100) at any spacing considered for this irrigation strategy. However, predicted yields were substantially reduced by soil salinity. Average relative yields were only 25% at a 15 m drain spacing. Yield dropped with increased spacing to 18% at the 100 m spacing.

Compared to the first strategy, the second irrigation strategy substantially increased predicted bean yields for narrow drain spacings (15-25 m). The increase was due to reduced stresses caused by soil salinity. For larger spacings (30-100 m), with lower drainage rates, excessive soil water and salinity conditions limited relative yields. Applying a 10 cm of leaching irrigation at one time before the growing season resulted in higher drainage rates than applying the same depth over the whole growing season.

1st Irrigation Strategy

Drain Spacing (m)	Excess (RY_w)	Relative Yield Deficient (RY_d)	Salinity (RY_g)	Overall (RY)
15	100	97	26	25
20	100	97	22	22
25	100	97	21	20
30	100	97	20	19
40	100	97	18	17
50	100	97	17	16
100	100	97	16	16

2nd Irrigation Strategy

Drain Spacing (m)	Excess (RY_w)	Relative Yield Deficient (RY_d)	Salinity (RY_g)	Overall (RY)
15	96	99	63	60
20	94	100	52	49
25	91	100	42	38
30	87	100	30	26
40	84	100	22	18
50	82	100	19	16
100	74	100	15	11

3rd Irrigation Strategy

Drain Spacing (m)	Excess (RY_w)	Relative Yield Deficient (RY_d)	Salinity (RY_g)	Overall (RY)
15	85	100	83	70
20	81	100	78	63
25	76	100	72	55
30	72	100	66	47
40	64	100	52	34
50	58	100	38	23
100	34	100	21	7

4th Irrigation Strategy

Drain Spacing (m)	Excess (RY_w)	Relative Yield Deficient (RY_d)	Salinity (RY_g)	Overall (RY)
15	94	100	96	90
20	89	100	92	83
25	69	100	89	61
30	47	100	87	41
40	13	100	89	12
5o	0	100	87	0
100	0	100	80	0

Table 2. Relative yield components (RY_w, RY_d, RY_g, and RY) for bean as a function of drain spacing for different irrigation strategies.

Hence, salinity was reduced and yields increased for the second strategy compared to the first one. For the third irrigation strategy (15 cm depth before the growing season) a rise in predicted yield due to salinity (RY_S) and a drop in predicted yield due excessive soil water conditions (RY_W) are shown in Table 2. Average relative yields for the third irrigation strategy were only 70% at a drain spacing of 15 m. Yield declined with increased spacing to 7% at the 100 m spacing (Figure 3). The fourth irrigation strategy applied leaching water both prior and during the growing season with a 14 rather 7 day irrigation interval. This additional leaching resulted in a significant decrease in soil salinity but increased stresses due to excessive soil water conditions for spacings of 25 m or more (Table 2). The predicted average yield for a 15 m spacing was 90% of the potential. Predicted yield dropped to 0% at a 100 m spacing due to excessive soil conditions (Table 2, Figure 3).

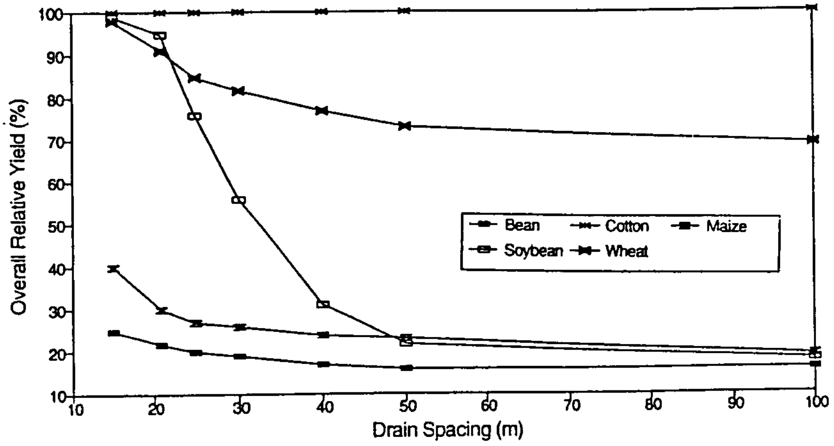

Figure 3. Average overall relative yield for bean as a function of drain spacings for four irrigation strategies.

Maize

Average predicted relative yield components (RY_W, RY_d, RY_S, and RY) for seven maize crops in the 19 year simulation period are given as a function of drain spacing in Table 3 for all irrigation strategies. For the first irrigation strategy, the yield reductions were primary due to high salinity in the root zone. Predicted relative yields were not greater than 40% for all drain spacings. Deficit soil water stresses reduced the yield somewhat with effect being greater at narrow spacing. Excessive soil water stresses did not limit yields at the narrow spacings but had a small effect for spacing greater than 40 m. Overall relative maize yields increased with improved drainage for the first irrigation strategy, as shown in Figure 4, but the maximum drainage intensity considered did not provide sufficient salinity control for acceptable yields.

1st Irrigation Strategy

Drain Spacing (m)	Excess (RY_w)	Relative Yield Deficient (RY_d)	Salinity (RY_g)	Overall (RY)
1S	100	86	46	40
20	100	91	32	30
25	100	94	29	27
30	100	95	27	26
40	99	96	26	24
50	97	97	25	23
100	94	97	21	19

2nd Irrigation Strategy

Drain Spacing (m)	Excess (RY_w)	Relative Yield Deficient (RY_d)	Salinity (RY_g)	Overall (RY)
15	100	81	57	46
20	100	85	46	39
25	100	89	39	35
30	100	90	35	32
40	100	92	30	28
50	100	93	28	27
1 (N)	100	94	24	22

3rd Irrigation Strategy

Drain Spacing (m)	Excess (RY_w)	Relative Yield Deficient (RY_d)	Salinity (RY_g)	Overall (RY)
15	100	81	98	80
20	100	87	93	81
25	100	90	88	79
30	100	92	83	76
40	100	93	71	66
50	100	94	58	55
100	100	95	23	22

Table 3. Relative yield components (RYW, RYd, RY" and RY) for maize as a function of drain spacing for different irrigation strategies.

Similar trends were obtained for the second irrigation strategy (Table 3 and Figure 4) with the salinity stresses being the dominant factor limiting the overall yield (RY). The highest yield obtained for second irrigation strategy was 46 % at 15 m drain spacing. A significant improvement in the overall yield was obtained for the third irrigation strategy. The additional water applied for leaching in this strategy substantially reduced soil salinity stresses for drain spacing less than 50 m. The highest overall relative yield for this strategy was 81% at 20 m drain spacing. Similar to the first strategy, as the drainage rates decreased with large spacing, overall yield dropped due to increased salinity stresses in the root zone (Figure 4), although stresses due to deficit condition were reduced slightly.

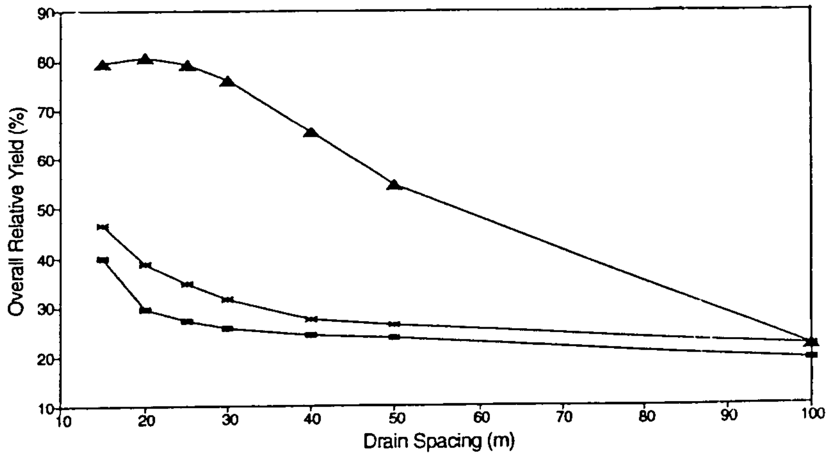

Figure 4. Average overall relative yield for maize as a function of drain spacings for three irrigation strategies.

Soybean

Average predicted relative yield components (RY_W, RY_d, RY_s, and RY) for soybean are given in Table 4 as a function of drain spacing for all irrigation strategies. Predicted overall yields are plotting in Figure 5. Applying 10 cm of leaching water during the growing season in the first irrigation strategy resulted in a 99% relative yield for a 15 m drain spacing. Wider spacings caused predicted yields to be reduced due to both excessive soil water conditions and increased soil salinities. Results for the second irrigation strategy show that applying the same amount of leaching water prior to the growing season is more effective than the first strategy for drain spacings greater than 15 m. Both soil salinity and stresses caused by excessive soil water conditions were reduced and yields increased compared to the first irrigation strategy, for drain spacings less than 30 m. Predicted average yields were 100% for a 20 m spacing with this irrigation strategy. The third irrigation strategy for soybean increased predicted relative yields for drain spacing up to 50 m (Table 3). A predicted average relative yield of 100% was predicted for a 30 m spacing with this irrigation strategy.

1st Irrigation Strategy

Drain Spacing (m)	Excess (RY_w)	Relative Yield Deficient (RY_d)	Salinity (RY_g)	Overall (RY)
15	100	99	100	99
20	100	99	96	95
25	93	99	83	76
30	81	99	70	56
40	66	99	46	31
50	55	99	39	22
100	22	99	19	4

2nd Irrigation Strategy

Drain Spacing (m)	Excess (RY_w)	Relative Yield Deficient (RY_d)	Salinity (RY_g)	Overall (RY)
15	100	100	100	100
20	100	100	100	100
25	100	100	95	95
30	100	100	73	73
40	100	100	41	40
50	100	100	30	30
100	100	100	21	21

3rd Irrigation Strategy

Drain Spacing (m)	Excess (RY_w)	Relative Yield Deficient (RY_d)	Salinity (RY_g)	Overall (RY)
15	100	100	100	100
20	100	100	100	100
25	100	100	100	100
30	100	100	100	100
40	100	100	94	94
50	100	100	65	65
100	40	100	29	12

Table 4. Relative yield components (RY_w, RY_d, RY_g and RY) for soybean as a function of drain spacing for different irrigation strategies.

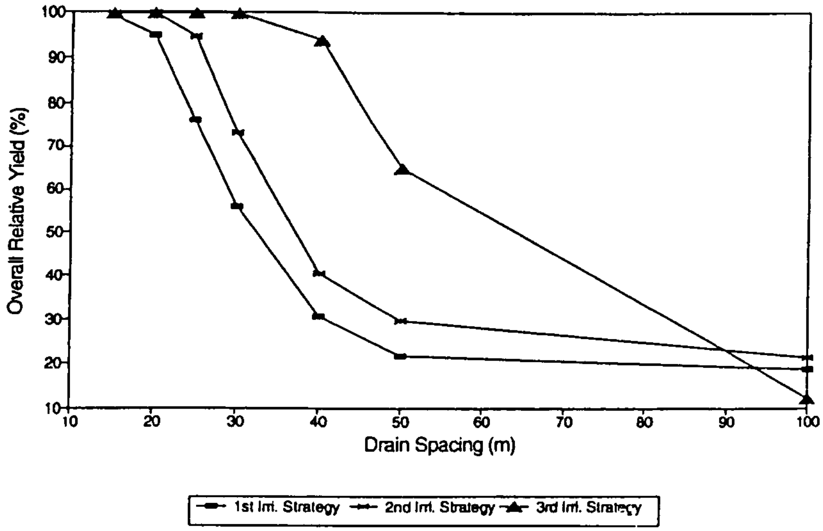

Figure 5. Average overall relative yield for soybean as a function of drain spacings for four irrigation strategies.

Wheat

The average predicted relative yield components (RY_w, RY_d, RY_s, and RY) for wheat are given as a function of drain spacing in Table 5 the all irrigation strategies. Overall predicted yields are plotted as a function of drain spacing in Figure 6. For the first irrigation strategy, the results indicate that soil water conditions in the root zone were favorable. Stresses due to neither excessive soil water nor deficit limited yield (i.e RY_w, $RY_d = 100$) at any spacing considered for this irrigation strategy. On the other hand, stresses due to soil salinity reduced yields for all spacing in this irrigation strategy. Soil salinity increased and yield decreased with drain spacing as shown in Table 5 and Figure 6. For the second and third irrigation strategies, where leaching depths were applied before beginning of the season, increased wheat yields were predicted for spacings less than 50 m (Figure 6). Applying the extra irrigation water at one time (second strategy) or applying more irrigation water prior to the growing season (third irrigation strategy) increased leaching in the profile and reduced salinity stresses for drain spacing less than 50 m. For the wider spacings third irrigation strategy resulted in stresses due to excessive soil water conditions and decreased overall yields at the 100 m spacing.

1st Irrigation Strategy

Drain Spacing (m)	Relative Yield			
	Excess (RY_w)	Deficient (RY_d)	Salinity (RY_g)	Overall (RY)
15	100	100	98	98
20	100	100	91	91
25	100	100	85	85
30	100	100	82	82
40	100	100	77	77
50	100	100	73	73

2nd Irrigation Strategy

Drain Spacing (m)	Relative Yield			
	Excess (RY_w)	Deficient (RY_d)	Salinity (RY_g)	Overall (RY)
15	100	100	100	100
20	100	100	100	100
25	100	100	100	100
30	100	100	98	98
40	100	100	89	89
50	100	100	73	73
100	100	100	66	62

3rd Irrigation Strategy

Drain Spacing (m)	Relative Yield			
	Excess (RY_w)	Deficient (RY_d)	Salinity (RY_g)	Overall (RY)
15	100	100	100	100
20	100	100	100	100
25	100	100	100	100
30	100	100	100	100
40	100	100	100	100
50	95	100	100	95
100	18	100	86	16

Table 5. Relative yield components (RY_w," RY_d, RYg and RY) for wheat as a function of drain spacing for different irrigation strategies.

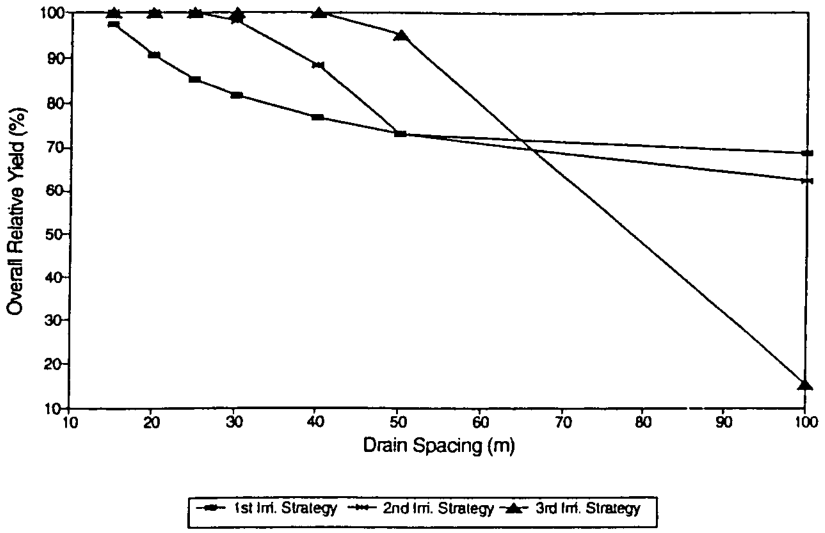

Figure 6. Average overall relative yield for wheat as a function of drain spacings for four irrigation strategies.

Cotton

Cotton is considered a salt tolerant crop with a threshold of 7700 mg/l (Mass and Hoffman, 1977). Stresses due to excessive soil water, water deficit, excessive soil salinity did not limit yield (i.e. RY=100) for all drain spacings and considered irrigation strategies. To study the effect of salinity build up on the yield of cotton, simulations were performed for a range of spacings without additional irrigation for leaching. That is irrigation amounts were set to just satisfy ET requirements with no additional water for leaching salts. The average predicted relative yield components (RY_w, RY_d, RY_s, and RY) for cotton are given in Figure 7 as a function of drain spacing. Excessive and deficit soil water stresses did not limit cotton yields at any spacing (i.e. RY_w and RY_d =100%). The salinity build up at the end of the simulation caused a drop in the yield due to salinity stresses. Predicted relative yield due to salinity (RY_s) were 93% and 73% for drain spacing of 15 and 100 m respectively.

Effect of Drain Depth on Crop Yield

Simulations were conducted to determine the effect of drain depth and spacing on crop yields using the fourth irrigation strategy for bean and the third strategy for maize. Predicted average crop yields as functions of drain spacing are plotted for drain depths (1.0, 1.2, and 1.4 m) in Figures 8 for bean and in Figure 9 for maize.

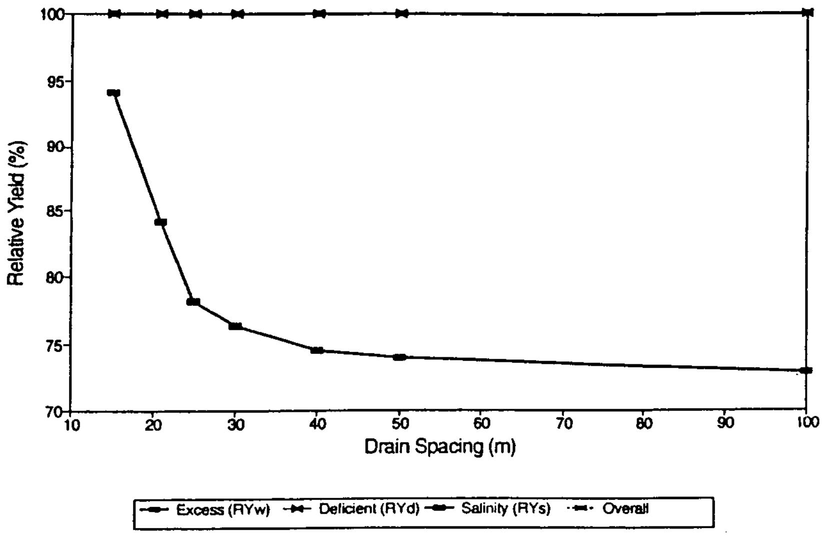

Figure 7. Overall relative yield for cotton as a function of drain spacings at the 19 years simulation period with no leaching irrigation applied.

The results show a strong interaction between depth and spacing. For bean, predicted yields increased with drain depth for a given spacing. Conversely, the same yield could be obtained at a wider spacing by increasing the drain depth. Similar results were obtained for maize. For example, by placing the drains 1.4 m rather than 1.0 m deep, the spacing could be increased from 15 to 25 m without decreasing maize yields (Figure 9). Another interaction is also demonstrated by the results of Figure 9. Predicted maize yields for a 1.4 m drain depth are less at 15 m spacing than for spacings of 20 and 25 m. Furthermore, it is less than the yield predicted for depth of 1.0 and 1.2 m at the same 15 m spacing. This reduction in yield is due to the fact that increased drainage intensity provided by the narrow (15 m) spacing and deeper drain depth (1.4 m) removed water that would have supplied ET. Deficit soil water stresses were increased and predicted yields reduced. Nevertheless, results in Figures 8 and 9 show that in general, salinity stresses can be reduced and yields increased by deeper drain depths.

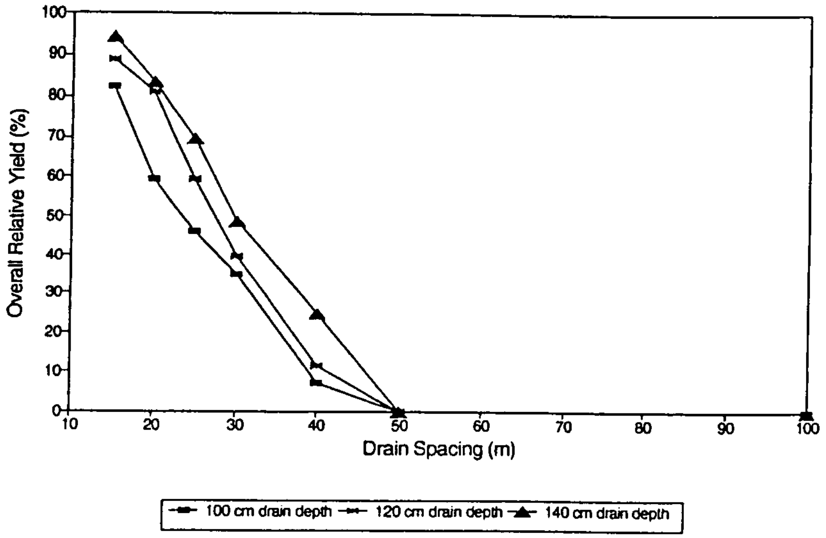

Figure 8. Average overall relative yield for bean as a fuction of drain spacing and depth using the fourth irrigation strategy.

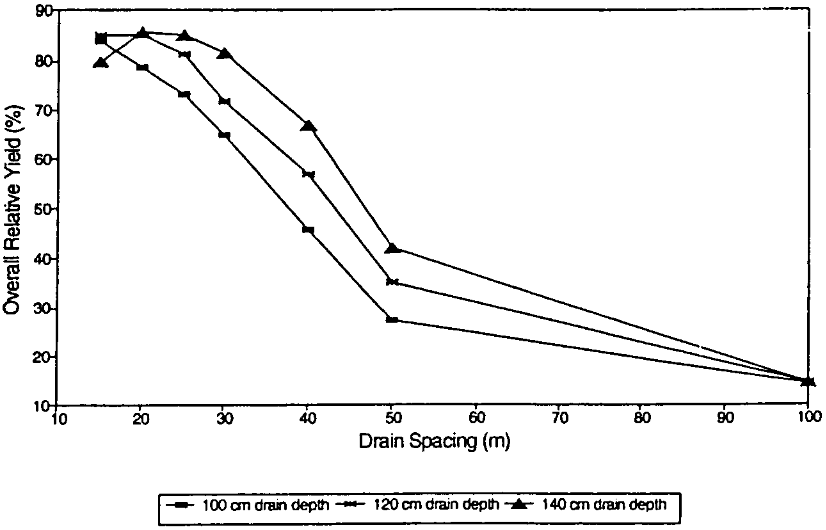

Figure 9. Average overall relative yield for maize as a fuction of drain spacing and depth using the fourth irrigation strategy.

Irrigation Strategy and Drainage Design

Results of simulation presented herein clearly demonstrate the interdependence of drainage requirements and irrigation strategy and management. This supports the often stated proposition that drainage and irrigation system for arid lands should be considered a component of a water management system and that the design and management of each component should depend on the other, rather than being treated as separated entities. Results given in this paper should that it was necessary to change the amount and timing of the application of irrigation water to provide effective leaching and achieve high yields for some crops (bean and maize) regardless of the drainage system design. For other crops the drain spacing could be increased, thus substantially reducing the cost, by changing the irrigation strategy. While the irrigation management can be changed to suit the needs of the individual crops, the drainage system must satisfy the need of all the crops. Drainage rates and leaching depend on drain depths on drain depth as well as spacing. Results in Tables 2-5 show that the third irrigation strategy--15 cm leaching depth before the growing season, gave the maximum yields for cotton, maize, soybean and wheat, while the fourth irrigation strategy gave the maximum yield for bean. Table 6 presents the drain spacing which gave maximum yield for each crop and its effect on the average relative yield of the other crops. For salt tolerant crops, cotton and wheat, the drain spacing required to maintain high overall relative yields were large compared to the optimum spacings for the other sensitive crops (bean, maize). A 15 m spacing would give the maximum yields for all crops except maize where the yield would be reduced by 1% from the maximum obtained using at a spacing of 20 m. A 20 m spacing would reduce relative bean yield by 7% but would give maximum yields for the other crops. A 30 m spacing would significantly reduce bean relative yield (from 90% to 41%) and reduce maize yields by 5% but would give maximum yields for other crops. Drainage systems represent sizable investments and design needed to maximize yields for all crops will be expensive and will not maximize profits. The problem gets more complicated with several crops being cultivated in a crop rotation as shown results in Table 6. Given the effect of drain spacing and depth on crop yields, an economic analysis should be conducted to determine the water management system design that would optimize long-term average profits.

	Optimum Spacing (m)		Relative Yield			
		Bean	Cotton	Maize (%)	Soybean	Wheat
Bean	15	90	100	80	100	100
Cotton	40	12	100	66	94	100
Maize	20	83	100	81	100	100
Soybean	30	41	100	76	100	100
Wheat	40	12	100	66	94	100

Table 6. Effect of each crop's optimum drain spacing on the other crops' overall relative yield, using the third irrigation strategy (15 cm leaching before the growing season).

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APPLICATION OF LINKED COMPUTER MODELS TO THE SIMULATION OF NITRATES IN SUBSURFACE DRAIN FLOWS

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ABSTRACT. Leaching of NO3-N in tile drain flow not only pollutes water resources, but can represent a significant economic loss for an agricultural enterprise. Potato *(Solanum tuberosum* L.) fields in eastern Canada present a considerable risk for NO3-N leaching, as they are grown on course textured soils and annual rainfall exceeds evapotranspiration by 300 to 400 mm. Computer simulation models are useful to develop management practices that minimize leaching, but they need to be validated with field measurements. Measured drain flow and NO3-N losses from two potato fields in Quebec were used to evaluate a linked drainage (DRAINMOD) and water quality (CREAMS) model. Predictions of drain flow varied between *+28%* and *-58%* of observed values for six site-years. Predicted NO3-N losses varied between +108% and - 41% of observed. The predicted NO3-N concentration in drain effluent was within 18~o of the observed average annual value, for three of four site-years. Predictions of NO3-N losses were highly sensitive to predicted depths of drainage.

INTRODUCTION

There is concern among the scientific community and the general public, that surface and ground waters in Eastern Canada are being contaminated by manure, fertilizers and pesticides. The possible impact of this contamination on human health and aquatic biota is unknown, both from the point of view of acute exposure to elevated chemical levels, and chronic exposure to low chemical concentrations. Lower fertilizer and pesticide application rates may reduce the risk of water pollution, but would likely decrease profitability of the agricultural enterprise (Kay and Baker, 1989).

A dramatic shift in cropping patterns has occurred, particularly in Quebec, where the area under continuous row crop production increased from 86,230 ha in 1971 to 450,000 ha in 1986. The introduction of subsurface drainage systems has encouraged this shift, as land which had previously been affected by a seasonally high water table, could now economically be brought into row crop production. The shift from small mixed farms to continuous row crop production has been accompanied by an increase in the use of fertilizers and pesticides. Therefore, the potential for the pollution of water resources has increased.

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The impact of nitrogen fertilizers on the environment is of particular concern, as they are reduced to soluble nitrate anions, which are easily leached from the soil profile. Nitrate-nitrogen (NO3-N) can either move to ground water, or return to streams via subsurface drain effluent. The presence of elevated NO3-N levels in aquifers, streams and lakes impairs these aquatic ecosystems, promotes increased eutrophication, and may render the water unfit for drinking. A number of studies has found that crops recover only 20 to 60% of applied fertilizer nitrogen (Miller and Mackenzie, 1978; Halberg, 1987 and references cited therein). Therefore, production systems which minimize the risk of offsite water pollution, yet maintain or enhance the profitability of agricultural production, must be developed.

Subsurface drainage is essential for the production of high value field crops in Eastern Canada. Annual precipitation exceeds evapotranspiration by 300 to 400 mm in the region. To date, approximately 2.5 million ha of land have been subsurface drained in Ontario, Quebec, and the Maritime provinces of Canada. Recent studies have reported NO3-N levels in drain effluent in excess of the Canadian Water Quality Guideline of 10 mg L^{-1} established for drinking water (Flemming, 1990; Milburn et al. 1990; Milburn and Richards, 1991; Madramootoo et al., 1992). Priddle et al. (1989) have reported elevated NO3-N levels in ground water under potato *(Solanum tuberosum* L.) fields on Prince Edward Island. This is of immediate concern, as all of the island's 127,000 residents rely on groundwater for drinking. Hill (1982) reported that 40% of the ground water near Aliston, Ontario had NO3-N concentrations in excess of 10 mg L^{-1}.

Many of the above studies were undertaken on potato cropped fields. Potato is a shallow rooted crop, which is usually grown on coarse textured soils. Applications of 110 to 180 kg ha^{-1} of nitrogen are required in Eastern Canada, for optimum yields. Given the limited water holding capacity of these soils, and the excess annual precipitation, leaching of NO3-N can be high. Cameron et al. (1978) reported nitrogen losses of 52 to 92 kg ha^{-1} yr^{-1} for potato. Hill (1986) reported that annual leaching losses of N from the top 183 cm of the soil profile in a potato field were 78 to 220 kg ha^{-1}. Losses of this magnitude may represent a significant financial loss for the agricultural producer.

Best Management Practices (BMP's) which reduce NO3-N leaching are required. However, extensive field studies are needed to evaluate alternative field management techniques. These are expensive, and require many years of experimentation. Additionally, results are site specific, and subject to short term climatic variations. This has led to the extensive use of computer simulation models for developing and assessing BMP's. However, simulation models must be carefully selected, as they are only applicable to specific conditions. These limitations arise because most models incorporate mathematical relationships which may be true only in the geographical or climatic region where they were developed. Therefore, models need to be tested for a wide range of soil, climatic and crop conditions, to ensure their validity. Otherwise, erroneous model results will lead to the improper selection of BMP's. The objective of this study is to evaluate a modified linked drainage (DRAINMOD) and water quality (CREAMS) model (Wright et al., 1992) for predicting NO3-N losses via tile drain effluent from a potato field in Quebec, Canada. Predicted drainage and nitrate leaching was compared with measured values.

MODEL BACKGROUND

A number of computer simulation models have been widely used for predicting soil erosion and water quality. These include CREAMS (Knisel, 1980), GLEAMS, (Leonard et al., 1987), ANSWERS, (Beasley et al., 1985), and PRZM (Carsel et al, 1984). ANSWERS and CREAMS have been developed for evaluating the impacts of agricultural practices on runoffand soil erosion. CREAMS also predicts surface water quality. GLEAMS and PRZM have been designed to simulate the rate and concentration of chemicals leached from the crop root zone. GLEAMS and ANSWERS have been tested in eastern Canada, and found to reasonably simulate field data (Masse and Prasher, 1989; Montas and Madramootoo, 1991). However, neither model simulates nitrogen leaching. CREAMS simulates nitrogen dynamics; both leaching below the root zone and losses associated with surface runoff. Several components of CREAMS have been tested with field data from cool humid climates. Rudra et al. (1985) found that the model gave reasonable estimates of the soluble phosphorus losses on a loam soil in southern Ontario. Jamieson and Clausen (1988) used CREAMS to predict monthly runoff, sediment and phosphorus exports from two agricultural fields in Vermont. The model over-estimated phosphorus losses during months when the observed flow was low, and under-estimated losses for high flow months. The inability of the model to accurately simulate snowmelt was also noted. Kallio et al. (1989) evaluated CREAMS for Finnish conditions. They modified the hydrology component of the model to account for snowmelt, as this is a major portion of the annual surface runoff in Finland. They found that erosion rates were over-predicted, and concluded that detachment of soil particles was not being properly modelled.

CREAMS consists of three sub-models, which simulate hydrology, soil erosion and soil chemistry. The model has a layered or "piggybacked" structure, in that the simulated water movement from the hydrology component is used as input for predicting soil erosion. Similarly, simulations from the hydrology and soil erosion submodels are used as input for predicting nutrient and pesticide losses. Given the model structure, it is apparent that errors in the simulation of water movement, or soil erosion, will be incorporated into the predicted chemical losses, and may result in erroneous prediction.

The CREAMS model simulates erosion and chemistry on an event basis. The model assumes that water leaches freely from the root zone whenever the water content of the soil exceeds field capacity. Bengston et al. (1985) and Enright and Madramootoo (1990) have reported that CREAMS under-predicts surface runoff during high water table conditions. The inability of CREAMS to simulate water table movement and tile drain flow is a shortcoming. Since most row crops in eastern Canada are grown on tile drained fields, usage of the model is limited to periods of the year when the water table is well below the soil surface, i.e., the summer months. Several researchers, including Milburn and Richards (1991), Kladivco et al. (1991), and Bergstrom (1987) have identified the fall and winter months (October to March) as the period when tile drain flows and leaching of nitrogen are highest. This, however, is the period for which CREAMS is not applicable, due to elevated water tables. One approach for overcoming this limitation has been the linking of CREAMS with a widely used drainage model.

DRAINMOD (Skaggs, 1978), is extensively used to design water management systems and predict water table response and drain flow for various water table management options. It is based on a water balance above and below the soil surface. The model simulates infiltration, evapotranspiration, surface runoff, subsurface drainage and water table position. DRAINMOD has been extensively tested (Skaggs et al., 1981; Fouss et al., 1987; Sanoja et al., 1990) and found to adequately describe drain discharge and water table position. The model produces output on a daily basis. However, it does not simulate water quality or soil erosion. Parsons and Skaggs (1988) replaced the hydrology component of CREAMS with DRAINMOD. The computer code for DRAINMOD was modified, so that it produced output on an event basis, and this was then input to the soil erosion and water quality submodels of CREAMS. The linked model was used to evaluate the effect of different drain spacings and water management practices on soil erosion. Simulated results were not compared with field data.

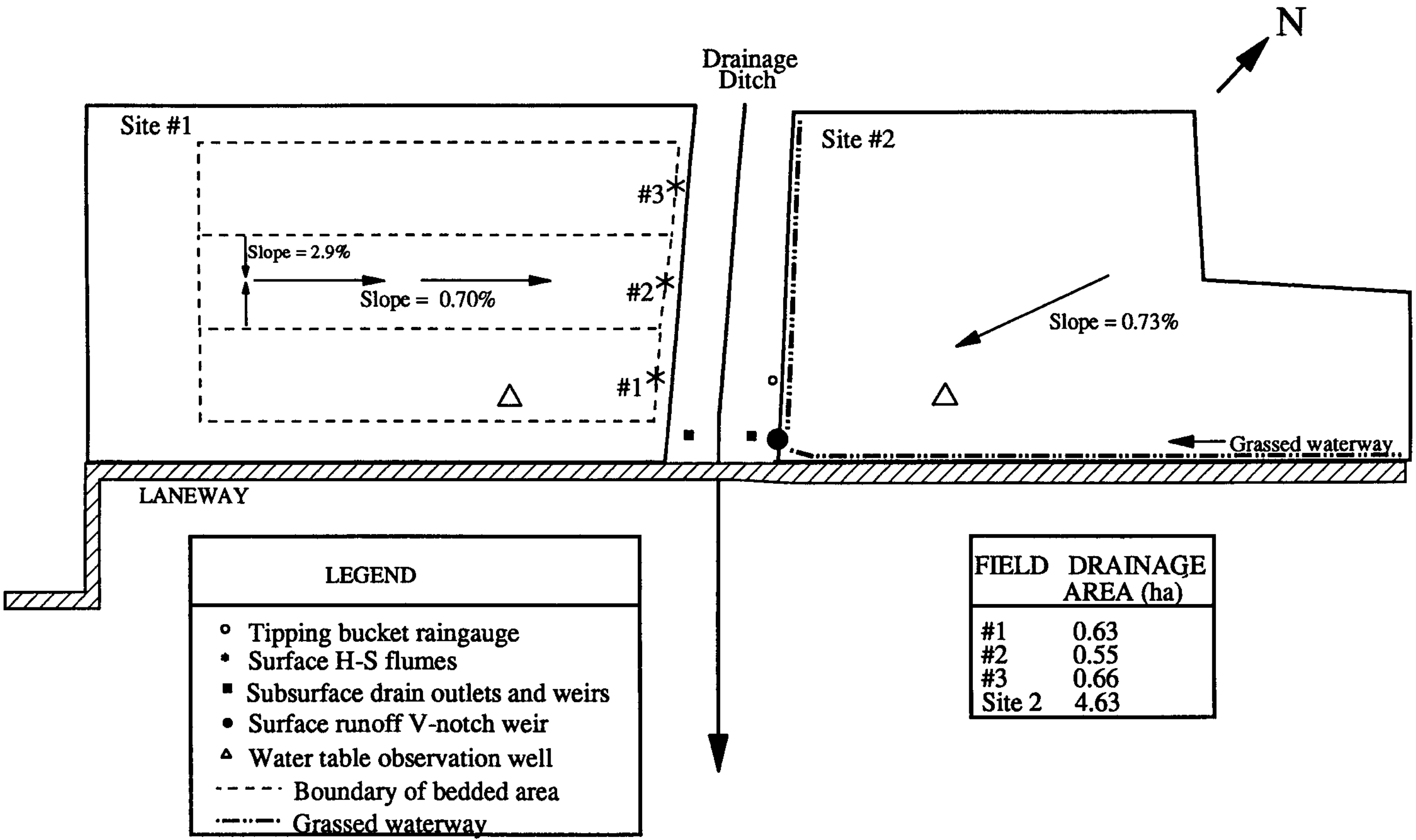
Wright et al. (1992) modified the denitrification component of CREAMS, and rewrote the computer code so that hydrology and chemistry were simulated on a daily basis. This version of the DRAINMOD-CREAMS linked model (DM-C) was tested using field data from Louisiana. Predictions of surface runoff, soil erosion, and nitrogen in surface runoff with DM-C were better than those obtained with the original linked model of Parsons and Skaggs (1988), or with the original CREAMS model. The DM-C model was then used to evaluate the effect of controlled drainage and subirrigation on NO3-N losses. However, model predictions of drain outflow and nitrate leaching were not compared with measured values. In cool humid climates, tile drain flow is the major component in the overall water balance, and is an important pathway for nitrogen losses. Therefore, this component of the model needs to be validated. To evaluate the suitability of the DM-C model for eastern Canadian conditions, field data were collected from a commercial potato farm. Predicted tile drain flows and NO3-N losses were compared with measured data.

MATERIALS AND METHODS

Field Site

A field site near St. Leonard d'Aston, Quebec (46°05' N lat., 72°24' W long.) was monitored between 1989 and 1991 (Fig. 1). Two subsurface drained potato fields, separated by a drainage channel, were instrumented to measure surface runoff and subsurface drainage. Site #1 was surface drained with cambered beds. These were developed over time by ploughing the land to form a crown, and a small drainage furrow between adjacent crowns. The furrows act as drainage channels. The slope from the crowns of the beds to the furrows varied from 1.8% to 2.9%. The slope along the length of the furrows was 0.7%. The drainage area of the beds ranged from 0.45 to 0.66 ha, and the length of the beds varied from 230 to 240 m. The spacing between bed center lines was 27 m. Three beds were instrumented with H-S flumes to measure surface runoff. Site #2 has a uniform slope of 0.73%, and a drainage area of 4.63 ha. The site was bounded by grassed waterways, which routed surface runoff from the edge of the field to the outlet. Surface runoff was measured at the downstream end of the field using a V-notch weir. The spacing between subsurface drainage laterals on site #1 was 30.5 m, and on site #2, 18.3 m. The depth of the drains was 1.2 m. The subsurface drainage outlets of both fields were equipped with V-notch weirs and water level recorders to monitor drain outflow. Water table observation wells with stage recorders were installed at both sites, at the midspacing between drainage laterals, to monitor water table position. On site #1, the observation well was installed near the crown of a bed. In this case, the depth of the drainage laterals from the soil surface were approximately 1.35 m..

Hydrologic measurements were made from April to December, during the study period. Instrumentation was installed during the summer of 1989, and monitoring continued until December, 1991. Rainfall was measured at the site using a tipping bucket raingauge and an electronic datalogger.



FIELD	DRAINAGE AREA (ha)
#1	0.63
#2	0.55
#3	0.66
Site 2	4.63

Schematic: not to scale

Figure 1. Site layout

Potatoes were grown during 1989 and 1990. On site #1, the variety planted during both years was 'Chieftain'. On site #2, the variety was 'Superior' in 1989 and 'Conestoga' in 1990. Both sites were planted to barley *(Hordeum uulgare* L.), and underseeded to clover *(Trifolum pratense* L.) during 1991. Table 1 lists the cropping and fertilizer application patterns for the fields during the study. Rates of N fertilizer application were consistent with those recommended by the Conseil des Productions Vegetales du Quebec.

Site	Year	Crop	Fertilizer applications	
#1	1989	Potato	1000 kg ha^{-1}, 10-12-18, 150 kg ha^{-1}, 34-0-0,	23/05/89 06/07/89
	1990	Potato	1500 kg ha^{-1}, 7-12-15, 100 kg ha^{-1}, 33-0-0,	20/05/90 27/06/90
	1991	Barley (clover) *	None	
#2	1989	Potato	1200 kg ha^{-1}, 10-12-18, 150 kg ha^{-1}, 34-0-0,	19/05/89 30/06/89
	1990	Potato	1350 kg ha^{-1}, 7-12-15, 105 kg ha^{-1}, 34-0-0,	14/05/90 25/06/90
	1991	Barley (clover) *	None	

* Barley, underseeded to clover

Table 1. Field histories

The soil type is a St. Jude sandy loam (Humo feric podsol). Soil particle size distribution was determined at the surface (0-10 cm), and below the plough layer (30-cm) on each site (Table 2).

Site	Sample Depth	Percent		
		Clay	Silt	Sand
#1	0-10 cm	2.9	9.5	87.6
	30-40 cm	0.6	2.5	96.9
#2	0-10 cm	5.3	21.7	73.0
	30-40 cm	8.4	33.7	57.9

Table 2. Measured soil texture

On site #1, sand content was found to be 88 % at the surface, and increased to 97% at 30 cm depth. On site #2, sand content was 73% at the surface, and it decreased to 58 % at 30 cm depth. The soil on site #2 had higher silt and clay contents compared to site #1, and was stony in some areas. The soil profile on site #1 was uniform with depth. However, on site #2, a highly compacted layer was found at a depth of 40-60 cm. It is likely that this has developed due to the intense machine traffic associated with potato production. Samples of tile drain effluent were manually collected during the 1989 and 1990 growing seasons. Triplicate grab samples were obtained according to the Water Quality sampling manual (Environment Canada, 1983). Samples were analyzed for NO3-N and NO2-N. Regular water sampling was discontinued during the autumn of 1990, due to financial limitations. However, during 1991, grab samples were obtained on three occasions, and analyzed using a portable spectrophotometer (Hach, 1989). Because of the reduced sampling frequency, estimates of the NO3-N leaching losses during 1991 cannot be made. Therefore, comparisons are presented for 1989 and 1990 only. A complete description of the sampling procedure and trends in nitrate concentrations with time are discussed in Madramootoo et al. (1992). To determine the monthly loss of NO3-N in drain water, the monthly drain discharge was plotted along with the measured NO3-N concentration. The NO3-N concentration on any given day was determined by interpolating between the two nearest sampling days. From this, daily loss of NO3-N in the tile drainage water were determined. Monthly totals were then calculated. The underlying assumption cm) on each site (Table 2). On site #1, sand content was found to be 88 % at the surface, and increased to 97% at 30 cm depth. On site #2, sand content was 73 % at the surface, and it decreased to 58~o at 30 cm depth. The soil on site #2 had higher silt and clay contents compared to site #1, and was stony in some areas. The soil profile on site #1 was uniform with depth. However, on site #2, a highly compacted layer was found at a depth of 40-60 cm. It is likely that this has developed due to the intense machine traffic associated with potato production. Samples of tile drain effluent were manually collected during the 1989 and 1990 growing seasons. Triplicate grab samples were obtained according to the Water Quality sampling manual (Environment Canada, 1983).

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Model inputs

Input parameters for the DM-C model were selected based upon measured field data, wherever possible. Climate, soil and plant par~meters were specified for the DRAINMOD component of the linked model, whereas the CREAMS component required estimates of initial nutrient availability and the pattern of nutrient uptake. **Climatological Data.**

Hourly rainfalls were determined from a tipping bucket raingauge located at the site. Daily maximum and minimum temperatures were determined for the St. Wenceslas weather station, located approximately 11 km north-east of the field site. Evapotranspiration (ET) was calculated by DRAINMOD, from the daily maximum and minimum temperatures. Monthly adjustment factors for ET were developed as suggested in the DRAINMOD 4.0 users manual. For an initial simulation, rainfall was artificially adjusted, so that soil moisture was never a limiting factor. The predicted monthly ET was compared with the long term observed ET, from the St. Wenceslas station. Predicted monthly ET had to be multiplied by 0.92, to match the long term average monthly ET.

Soil water characteristics

Moisture retention curves were measured at the two sites. Input parameters for DRAINMOD were developed using the DRAINMOD SoilPrep program. Drainable porosity *(f)* was determined from water table position and drain outflow measurements, and was found to be 0.09 for site #1, and 0.02 for site #2. The low value for *f* on site #2 indicates that the subsoil is quite compact. The relationships between water table position and drainable pore space calculated using the Soilprep software were then adjusted for the measured *f* values. The water table depth-upward flux relationship was also determined using the SoilPrep software.

Hydraulic conductivity

Hydrologic models are very sensitive to saturated hydraulic conductivity (K_{sat}) inputs. On these sites, extensive sampling was carried out to document the temporal and spatial variation of KBat. Core samples were obtained for the surface (0 to 10cm), and from below the plough layer (30 to 40 cm), and K_{sat} was determined using the falling head permeameter (Klute and Dirksen, 1986). The bulk density of each sample was also determined. A total of 293 samples were obtained during 1989-1990, on 5 sampling dates. The value of K_{sat} input to the model was determined by taking the logarithmic average of the K8at value obtained on each of the five sampling days (Table 3). On site #1, the soil profile was uniform with depth. Therefore, the K~at measured at the soil surface was deemed to be representative of the entire profile. On site #2, clay content increased with depth. The conductivity below the plow layer was determined using the auger hole method (van Beers, 1983). Seven measured values ranged between 0.10 and 1.42 cm hr^{-1}, with a mode of 0.61 cm hr^{-1} and a log. mean value of 0.64 cm hr^{-1}.

	Site #1		Site #2	
Sampling Depth	Bulk density g cm^{-3}	K_{sat} cm h^{-1}	Bulk density g cm^{-3}	K_{sat} cm h^{-1}
0 - 10 cm	1.31	2.83	1.32	1.08
30 - 40 cm	1.42	1.56	1.68	0.26

Table 3. Measured saturated hydraulic conductivities and bulk density

Plant Parameters

The rooting depth for potato in Quebec was obtained from Gallichand et al. (1991). Planting and harvesting dates, and yields were determined from the field records maintained by the farmer.

Soil erosion parameters

The erosion submodel of CREAMS requires a detailed description of the soil erodibility and field geometry. These were taken from work by Wiyo (1991), on the same sites. The measured depths of surface runoff on these sites were small, in comparison to the depth of drainage. Soil erosion was negligible.

Nutrient parameters

Organic matter content and total soil nitrogen were determined on both sites (Table 4). The dates and rates of fertilizer applications were determined from field records. Potential yield on the fields was established with the aid of the farmer, based upon previous crops. The documentation and software supplied with the CREAMS model was used to determine other model inputs, such as nitrogen and phosphorus extraction coefficients and exponents, and potential nitrogen uptake.

	Site #1		Site #2	
Sampling Depth	Organic matter content (%)	Total Soil N (μg g^{-1})	Organic matter content (%)	Total Soil N (μg g^{-1})
0 - 10 cm *	3.62	1277	3.68	1399
0 - 5 cm **	2.93	1390	2.77	1370
5 - 30 cm **	2.49	1170	2.86	1350

* Sampled 04/04/89, ** Sampled 15/05/90

Table 4. Measured organic matter and total soil N

RESULTS AND DISCUSSION

Simulated vs Observed Drainflow

The DRAINMOD component of the DM-C model was used to simulate drain outflow for the period 1989 to 1991. Table 5 shows the predicted and observed monthly, and annual depths of subsurface drainage. For all three years, the model under-predicted the depth of drainage from site #1, and over-predicted the depth of drainage from site #2. The under-prediction at site #1 is 28%, 48~o, and 58% of observed flows, for 1989, 1990 and 1991, respectively. Drain flow from site #2 was over-predicted by 27%, 28%, and 25%. The cumulative predicted and observed depths of drainage for the three years are shown in Figs. 2 and 3, respectively.

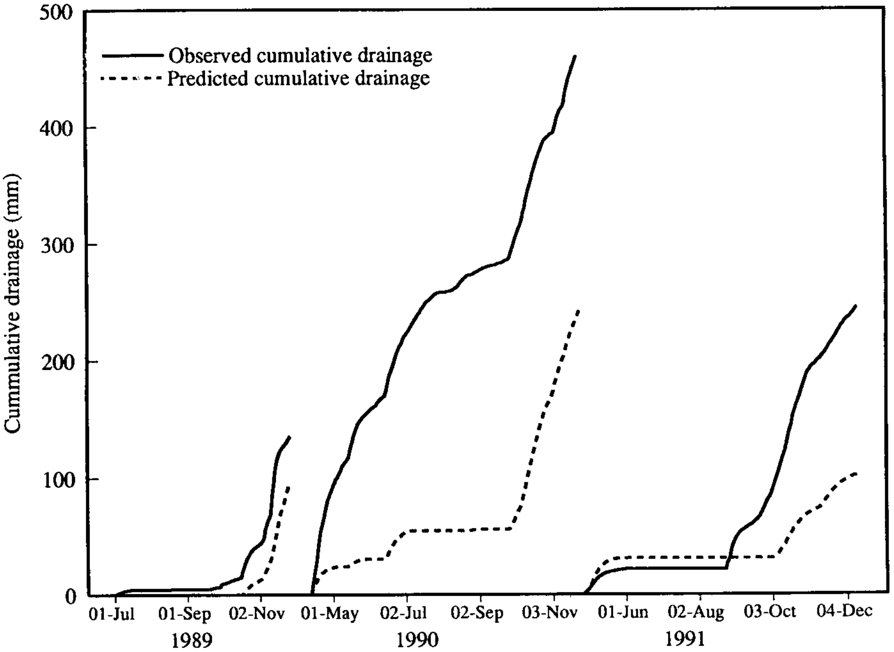

Figure 2. Observed and predicted cumulative drainage, site #1

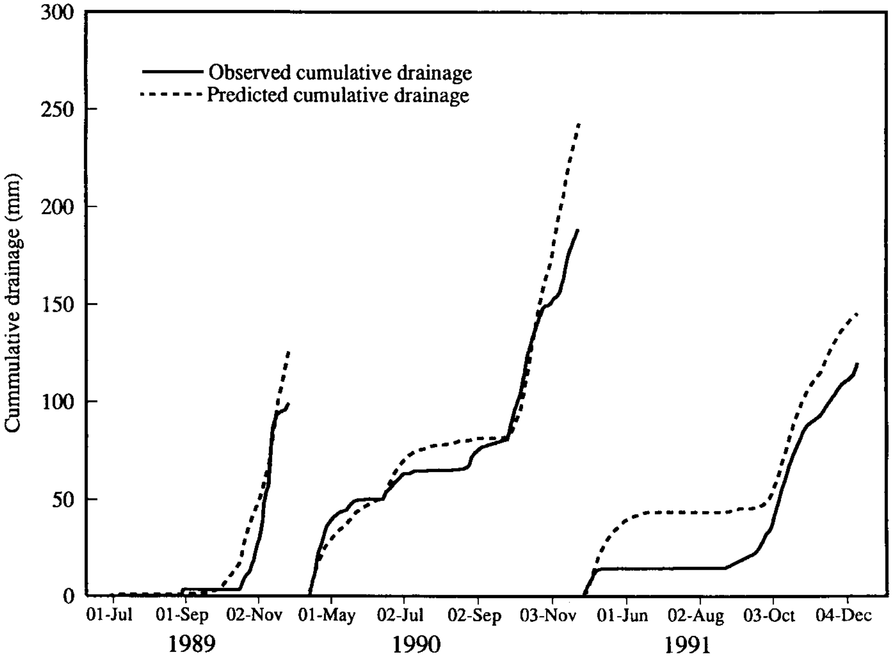

Figure 3. Observed and predicted cumulative drainage, site #2

On site #1, the model correctly predicted the absence of significant drain flow during the summer months of 1989. The sharp rise in drain flow during the autumn months was also correctly predicted. However, the model predicts drainage in the autumn at a later date than when drainage was observed. The summer of 1990 had above average rainfall, and consequently, the observed drain flow was very high. On site #1, the predicted depths of drainage for October and November, 1990 were close to the observed. However, the model under-predicted by a large amount the depth of drainage during the summer months. It is thought that the measured depth of drain flow at this site may have been overestimated, as there were measurement errors with the v-notch weir at this site. During the summer of 1991, predicted drain flow was close to the observed. However, model predictions for the autumn were less than the observed, and subsurface drainflow was predicted one month later than was observed.

Model performance on site #2 was better, both in predicting of the annual depth of flow and the seasonal pattern of drainage. Again, the model accurately predicted the absence of drain flow during the summer of 1989. During the fall of 1989, the depth of drain flow in October was over-predicted by a factor of 4, but November drainage was predicted within 3 mm (Table 5). Predicted drain flow from site #2 agreed well with the observed during the summer of 1990. However, during the fall of 1990, drain flow was over-predicted. This occured because surface runoff was under-predicted during the fall of 1990. During May, 1991, predicted drainage from site #2 exceeded the observed value. Predicted drain flow for the period of October to December is very close to the observed. However, during the autumn of 1991, observed drain flow begins earlier than is predicted, as on site #1. Between August 28 and 31, 1991, there were 10.1 cm of rain, and significant drain flow occured at both sites. On site #1, the model predicts drainage starting on October 6, while at site #2, only minor drain flow is predicted until late September. It is thought that this occurs because the water table depth-upward flux relationship specified in the model may have over-predicted the upward flux of water, and therefore, the depth of evapotranspiration was over-predicted. This resulted in under-predictions of soil moisture, and drain flow in the early fall.

Errors in predicting the depth of drain flow may occur because ET or infiltration, and subsequently, soil moisture is poorly modelled. Thooko et al. (1990) calibrated DRAINMOD, so that observed and predicted values are closely matched. They found that K_{sat},ET adjustment factors, rooting depth, and water table depth-upward flux and water table depth-drained volume relationships had to be adjusted on an annual basis. In this study, no effort was made to calibrate input parameters. Inputs were based solely on measured data, wherever possible. However, it was observed that improved predictions of cumulative drainage could be obtained if the DRAINMOD component of the model was used on a year by year basis, and simulations were started on April 1. Initial water table depths were adjusted based on field measurements. This indicates that the model does not adequately represent infiltration, and subsequent changes in soil moisture and water table position, that occur during snowmelt. Therefore, the simulated soil moisture and water table position in the late winter does not reflect actual field conditions. This occurs because the model lacks a snow accumulation/snowmelt component. It was found that manually adjusting rainfall in late March, to reflect snowmelt, improved the model performance.

There were some inconsistencies in the manner in which the original DRAINMOD and the linked DM-C model dealt with simulations which started on dates other than January, 1. Therefore, input for the CREAMS component of DM-C model was developed by simulating continuously for the period January, 1989 to December, 1991.

		Site #1		Site #2	
Year	Month	Observed	Predicted	Observed	Predicted
		Monthly drain flow mm month $^{-1}$		Monthly drain flow mm month $^{-1}$	
1989	Jul	4.6	0.0	0.2	1.1
	Aug	0.4	0.0	0.0	0.0
	Sep	1.9	0.0	3.3	2.1
	Oct	33.7	10.6	14.9	39.0
	Nov	95.1	87.1	80.9	83.5
	Total	135.6	97.7	99.2	125.7
1990	Apr	84.1	19.9	36.2	24.3
	May	69.4	8.0	13.8	19.3
	Jun	59.7	20.4	10.6	20.6
	Jul	44.5	4.0	4.5	11.1
	Aug	17.0	1.0	7.3	3.2
	Sep	13.9	1.1	11.1	1.5
	Oct	100.0	102.5	65.8	80.2
	Nov	71.1	82.7	38.8	80.0
	Total	459.6	239.6	188.1	240.2
1991	May	19.5	31.2	12.1	38.0
	Jun	0.8	0.1	0.1	5.7
	Jul	0.0	0.0	0.1	0.0
	Aug	13.5	0.0	1.5	0.6
	Sep	42.2	0.0	15.9	4.5
	Oct	99.6	34.6	52.6	52.1
	Nov	48.3	27.8	22.3	33.5
	Dec	19.1	8.0	10.9	10.4
	Total	243.1	101.7	115.6	144.8

Table 5. Observed and predicted depths of subsurface drainage

Simulated vs Observed surface runoff

Surface runoff was observed at site #1 on only three occasions during the study period. In all cases, the depth of runoff was less than 6 mm. These events resulted from short duration, high intensity storms. The DM-C model predicted that no surface runoff occured at site #1.

Table 6 shows the measured and predicted surface runoff at site #2. Runoff was under-predicted for all years. Surface runoff during the summer months occurred from high intensity, short duration storms. However, the largest depths of runoff were recorded during the autumn months, when elevated water tables resulted in surface runoff from long duration, low intensity storms. Poor predictions of surface runoffduring the autumn months occurred due to errors in modelling the water table position, which resulted from errors in the water table depth-drained volume relationship. Both the water table depth-drained volume, and water table depth-upward flux relationships were developed from the measured moisture retention curves. It is likely that the limited number of curves developed did not adequately represent the spatial and temporal variations that existed within the field. The under-prediction of surface runoff, especially during the autumn of 1990, resulted in an over-prediction of drain flow on site #2.

2.3 Simulated vs Observed Nitrate leaching

The CREAMS component of the DM-C model predicts drainage and NO3-N losses below the root zone. However, the DRAINMOD component of the linked model predicted the depth of drain outflow. On a short term basis, the depth of water moving below the root zone and that leaving the field in the tile drains may not be the same, because of changes in water table elevation, or changes in soil moisture between the bottom of the root zone and the drains. Also, some of the water which moves below the root zone may eventually move upwards by capillary rise. On a long term basis, we would expect the two values to be the same, as any change in storage will be small compared to the drainage volume.

In order to compare model predictions with the observed field data, we have to assume that the water and NO3-N leached below the root zone is not significantly different from that which appears in the tile drains. It was found that predictions of the depth of drainage below the root zone obtained with the CREAMS component of the model were essentially the same as the predited drainflow, when compared on a monthly basis. Therefore, it was concluded that predicted losses at the bottom of the root zone could be compared with losses measured at the drain outlet.

Table 7 shows the predicted NO3-N losses at the bottom of the root zone, and the observed NO3-N losses in the tile drain effluent. The total annual losses from site #1 were under-predicted by 41% and 29%, for 1989 and 1990, respectively. At site #2, the predicted nitrate leaching was greater than the observed by 108% in 1989, and 61% in 1990. For site #1, predicted monthly values were less than the observed values for both the spring and fall. In one month (June, 1990), the predicted value was greater than the observed. Predicted leaching losses during this month were high, in response to a rainstorm of 6.69 cm on June 19, 1990. At the time of seeding (May 20, 1990), 106 kg N ha^{-1} were applied. Because significant uptake of N does not nccur until after the middle of June. the N fertilizer is assumed to be easily leached. Actual leaching losses were less than half of the predicted losses. This would indicate that fertilizer may have been immobilised by microbial activity, or that drain flow was occurring partially as a result of macropore flow, and therefore, only a portion of the applied nitrogen fertilizer was subjected to leaching.

Year	Month	Observed	Predicted
		Surface runoff mm month^{-1}	
1989	Apr	1.8	8.6
	May	4.2	0
	Jun	6.8	0
	Jul	0.8	0
	Aug	0.0	0
	Sep	0.0	0
	Oct	15.0	7.0
	Nov	22.6	18.7
	Total	51.2	34.3
1990	Apr	-- *	0
	May	--	0
	Jun	9.4	0
	Jul	0	0
	Aug	1.8	0
	Sep	2.6	0
	Oct	11.4	8.1
	Nov	18.5	0.2
	Total	43.7	8.9
1991	May	--	0
	Jun	0	0
	Jul	0.3	0
	Aug	1.6	0
	Sep	0	0
	Oct	13.6	0
	Nov	0	0
	Dec	--	0
	Total	12.5	0

* Missing data

Table 6. Observed and predicted depths of surface runoff on site #2

Month	Site #1		Site #2	
	Observed	Predicted	Observed	Predicted
	NO_3-N losses kg ha^{-1} month^{-1}		NO_3-N losses kg ha^{-1} month^{-1}	
Jul, 1989	2.1	0	0	0.7
Aug, 1989	0.1	0	0	0
Sep, 1989	1.2	0	0.1	1.0
Oct, 1989	10.6	3.4	4.7	23.7
Nov, 1989	32.4	24.0	25.5	37.6
Total 1989	46.2	27.4	30.3	63.0
Apr, 1990	22.4	12.4	5.6	16.3
May, 1990	15.5	5.7	1.8	15.6
Jun, 1990	12.3	30.5	2.1	22.9
Jul, 1990	10.9	4.7	0.9	9.0
Aug, 1990	3.8	0.2	2.0	0.3
Sep, 1990	2.7	0.0	3.2	0.0
Oct, 1990	21.8	10.0	23.7	8.5
Nov, 1990	15.9	11.1	13.2	12.1
Total 1990	105.3	74.6	52.5	84.7

Table 7. Observed and predicted NO_3-N losses

At site #2, nitrate leaching was over-predicted in the fall of 1989 and spring of 1990. However, it was under-predicted for the fall of 1990. Poor predictions of nitrate leaching can arise due to errors in predicting drain flow, or because of errors in predicting the concentration of NO3-N in drainage waters. To assess the performance of the CREAMS component of the DM-C model, the predicted and observed NO3-N concentrations in the drainage waters can be compared. If on an annual basis, the total mass of leached nitrogen is divided by the depth of drainflow, the average annual NO3-N concentration is obtained. In this manner, errors due to inaccuracies in predicted drain flow are eliminated. Table 8 shows these values. The average annual concentration is predicted ±18 % for three of the four site-years. It is unclear why, on site #2, during 1989, concentration is over predicted by 65 %. It is possible that the initial values input for the nutrient component may have been inappropriate. However, the input parameters for site #1, which were selected in a similar fashion, gave good results.

During 1991, several grab samples were collected. The NO3-N concentration in these samples were very low, for several reasons. Firstly, the field had been planted to barley, and underseeded to clover. This combination results in complete ground cover and crop growth, into the late fall. Water and nutrient uptake is greater than with potato, and therefore, NO3-N leaching is less. Additionally, no fertilizer was applied to the crop, and the summer of 1991 was hotter and drier than the two previous years. Therefore, the depth of drain flow was small, and there was less potential for leaching. The average nitrate concentration measured in the grab samples was 9.6 mg L^{-1} and 7.9 mg L^{-1} respectively, for sites #1 and #2. The DM-C model was sensitive to these changes in cropping and fertilizer pattern, and the predicted concentration, on an annual basis, was 11.4 mg L^{-1} for site #1, and 12.9 mg L^{-1} for site #2.

	Site #1			Site #2		
	Observed drainage depth mm	Observed	Concentration * mg L^{-1}	Observed drainage depth mm	Observed NO$_3$-N Losses kg ha^{-1}	Concentration * mg L^{-1}
1989	135.6	46.3	34.1	99.2	30.3	30.5
1990	459.6	105.3	22.9	188.1	52.5	27.9
	Predicted drainage depth mm	Predicted NO$_3$-N Losses kg ha^{-1}	Concentration * mg L^{-1}	Predicted	Predicted	Concentration * mg L^{-1}
1989	98.0	27.4	28.0	125.0	63.0	50.4
1990	283.0	74.5	26.3	272.0	84.7	31.1
Difference between Observed and predicted 1989		-41 %	-18 %		+ 108 %	+65 %
1990		-29 %	15 %		-61 %	+11 %

Table 8. Observed and predicted NO$_3$-N concentration in drainage water

CONCLUSIONS

The DM-C model of Wright et al. (1992) was used to simulate drain flow and nitrate-nitrogen (NO3-N) losses in tile drainage water on two commercial potato fields for a three year period. Model inputs were developed from measured data wherever possible. Annual and monthly predictions of drain flow and nitrogen losses were compared with measured values. The following conclusions were drawn:

- The model under-predicted the annual depth of drainage at site #1 for all years, and over-predicted the depth of drainage at site #2. Over-prediction on site #2 occured because surface runoff was under-predicted. For four of the six site-years, predicted annual drain flow was within 30 % of observed. Monthly prediction of drain flow were highly variable.

- Predictions of the annual losses of NO3-N in tile drain effluent varied between +29 % and + 108%, for four site-years. Predictions of the average annual nitrate concentration in drainage water were determined, and were found to be between +65 % and 18 % of observed concentrations. Errors in predicting the annual NO3-N losses are a combination of the error in predicting drain flow, and the error in predicting NO3-N concentration. The data indicate that errors in predicting drain flow are of a greater magnitude.

- Variations between predicted and observed drain flow and NO3-N losses were greater for the monthly than annual values. This indicates that the model may not give reliable predictions of nitrogen losses for short periods of time, even if it is adequate for annual simulations.

- The performance of the model in its current state does not appear to be suitable for predicting nitrate losses, without prior calibration. Using the model to evaluate impacts of management practice for specific fields would require calibration of soil parameters, to better simulate drain flow.

ACKNOWLEDGEMENTS

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SI-DESIGN: A SIMULATION MODEL TO ASSIST WITH THE DESIGN OF SUBIRRIGATION SYSTEMS

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ABSTRACT. SI-DESIGN is a computer model developed to assist in the design of subirrigation systems. The model allows designers to calculate a design rainfall, underground pipe lateral spacing and collector pipe diameters for desired system performance. The model includes an economic analysis module to evaluate alternative designs on the basis of economic return.

The model allows the user to determine the economically optimum underground pipe lateral spacing for both subsurface drainage and subirrigation modes. A steady state saturated groundwater flow formulation is used to determine lateral spacing needed for subsurface drainage and, during subirrigation, to maintain the water table at design depth during peak evapotranspiration without rainfall. Collector pipes are sized for steady state conditions. The model introduces the concept of "watertable fluctuation index", wfi. The wfi parameter quantifies water table fluctuation and can be used to relate subirrigation system performance to crop yield.

The model is operational on IBM compatible microcomputers and is interactive and user friendly. The model has been extensively tested against field measurements and by thirty design professionals.

RESUME. *SI-DESIGN est un modèle informatique développé pour aider dans l'étude des systèmes d'irrigation souterraines. Le modèle permet de faire l'étude pluviomètrique des tuyeaux souterrains et des diamètres des tuyaux collecteurs afin d'avoir la performance désireé. Le modèle permet l'évaluation de différentes études sur des bases économiques.*

Le modèle permet a l'utilisateur de déterminer l'espacement latéral pour le drainage et l'irrigation souterraines. Une formule de courant continue d'eau souterraine est utilisée pour déterminer l'espacement latéral désiré au drainage souterrain et pendant l'irrigation souterraine, pour maintenir le niveau d'eau à la hauteur d'étude pendant le sommet de l'évaporation et de la transpiration sans pluie. La dimension des tuyaux collecteurs est choisie pour les conditions de courant continue d'eau. Le modèle introduit le concept de " Water table fluctuaction index", wfi. Le paramètre wfi quantifie la fluctuaction du niveau d'eau et il peut être utilisé pour lier la performance du système d'irrigation souterraine à la moisson.

Le modèle s'utilise sur les ordinateurs compatibles avec IBM. Il est interactif et d'utilisation facile. Le modèle a aussi bien été prouvé par des résultats sur le terrain que par trente professionnels dans le domaine d'étude de systèmes d'irrigations souterraines.

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INTRODUCTION

Water table management

Many agriculturally productive soils have a naturally occurring shallow water table that fluctuates during the growing season. For centuries agricultural producers have used underground drainage pipe systems to improve crop production by removing excess soil water from within the root zone. Agricultural producers and scientists have recently shown that underground drainage pipe systems can also be used to provide water to crops during rainfall deficit periods and improve production by reducing deficit water stress. Underground drainage pipe systems that have the capability of removing subsurface water when the root zone is too wet for optimum biomass production and providing subsurface water to prevent root zone water deficiency are called subirrigation systems.

For many crops and soil textures, experience and research have shown a constant 0.8 to 1.2 m depth to the water table is near the optimum for corn production (Goins et al., 1966; Williamson and Kriz, 1970). However, when rainfall during the growing season is less than the volume needed by the crop, the water table falls below the 1.2 m depth and water deficit stress can reduce biomass production. This deficiency may be overcome by irrigation. However the economic return on irrigation system investment via traditional sprinkler type systems is limited due to the fact that relatively high average yields can be obtained without irrigation.

Through field research (Belcher, 1989) it was confirmed that corn and soybean production is sensitive to mean water table depth and water table fluctuation. That research suggests the best operation strategy for subirrigating field crops is: (1) establish a water table at design depth immediately following seeding, (2) maintain that depth until crop maturity, (3) at crop maturity initiate operation of the system in the subsurface drainage mode and maintain it in that mode until after harvest, and (4) repeat the cycle the next spring.

A water table management system that combines subirrigation with subsurface drainage potentially provides an ideal soil moisture regime in the root zone. A system operating in the subsurface drainage mode drains excess water from the root zone following rainfall events. The system operating in the subirrigation mode (see Figure 1) establishes and maintains a water table near the bottom of the crop root zone from which water moves by capillarity into the root zone thus preventing stress due to water deficit. Because capillarity is a function of soil water tension which is a function of the less than saturated soil water content, the plant controls the irrigation rate and timing. In other words, for a constant depth to the water table, the irrigated plant itself schedules the irrigation based upon its physiological needs. This suggests that the optimum water table management strategy, for biomass production, is to maintain the water table near the soil surface from time immediately after seeding to germination; allow the water table to fall, at the optimum root length development rate, to an optimum depth for the crop; and the maintain the water table at that depth until the crop matures. Thus, the system for optimum production will have pipe sizes large enough to drain excess water at the maximum rainfall rate and provide subirrigation water at the maximum evapotranspiration rate. In addition, the pipe laterals will be spaced so as to allow for saturated flow to midway between pipes at maximum rainfall rate and maximum evapotranspiration rate with only slight water table surface elevation difference.

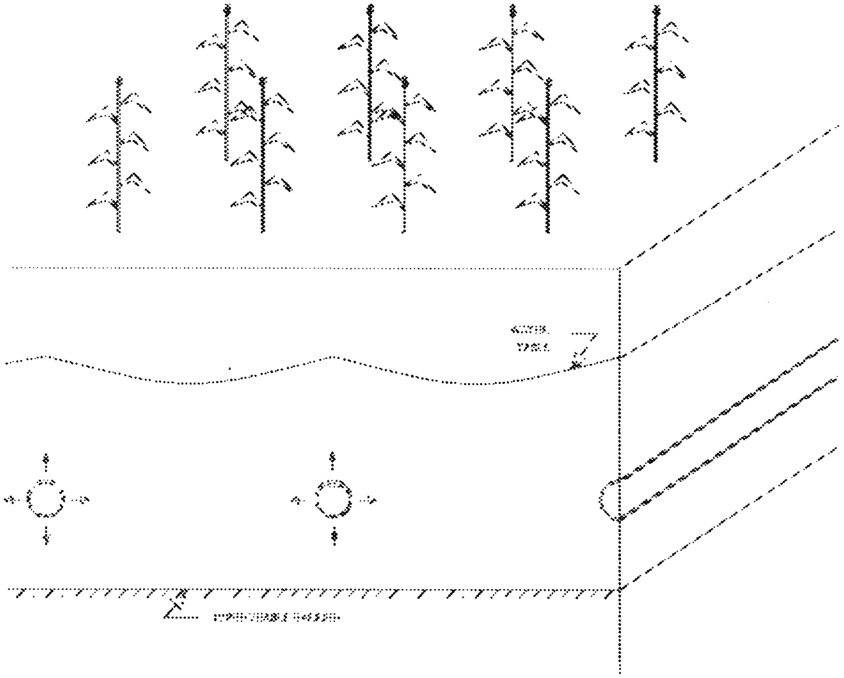

Figure 1. Cross sectionnal schematic of a water table management system operating in a subirrigation modele.

Subirrigation system design methods

The design methods used to establish pipe depth, spacing and flow capacity in a water table management system are established for a specific site by one or a combination of three methods.

Most often parallel pipe spacings are established by modifying the spacing that would have been used at the site for subsurface drainage. Frequently the recommended subsurface drainage spacing is multiplied by 0.66. Doty et al. (1986) suggested adjustments to the multiplication factor based upon the United States Department of Agricultural (USDA) classification for the soil in the profile.

A second method of determining lateral spacing is to calculate the spacing using a modification of a steady state equation developed by Hooghoudt and Ernst (van Beers, 1976).

Computer simulation of water table management system performance, the third method, has been shown to be applicable to the design process. Simulation models vary in complexity, input data requirements, and ease of use. Examples of computer simulation models being used are DRAINMOD (Skaggs, 1978), the SWATRE model (Feddes et al., 1978; Belmans et al., 1983) and the WATRCOM model (Parsons, 1987).

DRAINMOD is based on a one-dimensional (vertical) water balance within the soil profile and at the soil surface. The SWATRE model is based upon solving the Richard's equation for combined saturated-unsaturated flow in the vertical direction. For drainage system design, the SWATRE model is linked with other models to predict trafficability, germination, emergence, crop growth and production (van Wijk and Feddes, 1986). The WATRCOM model links a finite element solution of the two-dimensional Boussinesq equation for the saturated zone below the water table with a vertical water balance for the unsaturated zone above the water table.

DRAINMOD is used for design in the United States. The applicability of the model for that purpose has been documented by Mostaghimi et al. (1985), Evans and Skaggs (1987) and others.

Computer simulation models have the capability of allowing the system designer to design for a site on the basis of transient system operation and economic return on investment. However, because their use requires multiple runs and detailed soil and weather data often not available, application of these models for water table management system design has been limited.

The key element of the design of a water table management system is to determine the lateral spacing and pipe sizes that limit reduction in yield due to fluctuation of the water table following rain events in terms of benefit and cost. In other words, how close should the laterals be spaced to obtain the maximum return on the system cost when a rainfall event occurs while in the subirrigation mode.

The SI-DESIGN computer model was developed to provide subirrigation system designers with a method of rapidly determining how varying subirrigation system design parameters effect system performance and economic return on investment.

MODEL SPECIFICATIONS

Hardware requirements

SI-DESIGN has the following requirements and attributes:

1. the model is operational on the following minimum system configuration:

   - IBM personal computer or compatible with a minimum of 256 k RAM memory and a fixed disk;
   - CGA or higher resolution monitor, monochrome or color;
   - 80 character line printer;

2. model operation is interactive with the user responding to prompts displayed on the monitor; and

3. the model does not require additional software other than the operating system software (MSDOS or PCDOS Version 3.1 or higher).

Model format

The model is in modular format and includes the following modules: SETUP, RAIN, LSPACE, MAIN, COST, and ECON. The model is interactive and user friendly. Modules are selected from a menu. The modules are independent of each other. Each module has a Commands Menu that provides the options of analyzing data, displaying help screens, loading data files, printing results, saving the input data as a disk file, executing DOS commands and returning to the main menu.

MODULE DESCRIPTIONS

Setup

SETUP is used to customize the model for the user's hardware. SETUP options include english or CGS units, display colors, and monitor graphics capabilities.

Rain

The RAIN module calculates the design rainfall event to be used for subsequent modules. RAIN uses historic growing season rainfall records provided by the model user as a text file.

The input data include number of years to be analyzed, growing season start date and end date, and daily rainfall for each day of the growing season of each year.

The module uses the input data to calculate and output the 50% probability (2 year recurrence interval) and 10% probability (10 year recurrence interval) daily rainfalls by month and growing season. The module also calculates the number of rainfall events per month and growing season at the 50% probability level.

To calculate the 50% and 10% probability daily rainfalls, the historic growing season daily rainfall data is ranked in decreasing order, excluding 0 rainfall days, and the recurrence intervals are calculated by a partial series duration analysis described by Chow (1964).

LSPACE

A water table management system consists of perforated underground pipe spaced at regular intervals. These pipes are called laterals and are arranged in zones determined by the elevation variance of the soil surface within the zone. Laterals within each zone discharge to an underground collector pipe called a submain. The submain for each zone outlets to an underground pipe called a main. The number and size of zones, submains and mains is a function of the topography of the site.

Each zone requires a water table control structure located in the submain immediately downstream of the zone. The water table control structure has the capability to be set to allow free drainage (subsurface drainage mode) or to establish a water table upstream of the structure at a desired elevation (controlled drainage mode and subirrigation mode). Irrigation intake structures, vertical pipes from the submain to the ground surface, are provided for irrigation water access to the underground system during times when rainfall does not maintain the water table at the desired elevation. The irrigation water is pumped from the source to the field through irrigation water supply pipes.

Research reported by Belcher (1989) suggests that system operation must consider both the depth to the water table during the growing season and the fluctuation of the water table. Furthermore , the research suggests that water table fluctuation has a greater effect on yield than does mean water table depth.

The water table system components that limit control of depth to the water table and rate of fluctuation are depth, spacing and hydraulic capacity of the laterals; hydraulic capacity of the submains and mains; operational capability of the water table control structures; and hydraulic capacity of the water supply system.

The LSPACE module allows for investigating the combined effects of those components on the functioning of subirrigation systems. Thus the user is able to evaluate the effects of system design alternatives on system performance in terms of water table depth and water table fluctuation.

User input data describe the soil profile, the design rainfall event, system components, and system operation. The model uses the input data to compute and report the lateral spacing and discharge capacity required for steady state supply of irrigation water and subsurface drainage. Next, the vertical rise of the water table due to infiltration of the design rainfall -runoff is calculated. This is followed by transient analysis to determine the time and discharge rates for the water table to return to the levels preceding the rainfall event.

LSPACE consists of five sections: data input, initial calculations, steady state analysis, transient analysis and output of results.

Input data

Input data that describe the subirrigation system are depth, diameter, minimum grade and average length of the lateral pipes. The user also provides the desired depth to water table at the lateral and at midway between laterals for both subirrigation and subsurface drainage modes. Finally, the subirrigation and subsurface drainage design rates, design storm rainfall, design storm rainfall occurrences per season, and depth at which the weir will be set following rainfall events are provided.

The soil parameters provided are depth to the impermeable barrier; number of soil layers in the soil profile; and layer thickness, saturated hydraulic conductivity, water content at saturation, and water content at drained upper limit, for each soil layer.

The required input data, for the most part, are self explanatory and are easily obtained. The water content at saturation (sat) is the volumetric soil water content when the soil is saturated. The drained upper limit (dul) is the volumetric water content that results from complete soil water drainage from the layer without evaporation or transpiration. The sat and dul terms are described further by Ritchie, et al. (1986).

Steady state analysis

Infiltration, for the design storm event, is calculated by subtracting runoff from rainfall. Runoff is calculated using the USDA Soil Conservation Service curve number method (USDA Soil Conservation Service, 1972). Then, the model calculates a weighted value for saturated hydraulic conductivity and the difference in the volumetric water contents at saturation and drained upper limit.

LSPACE calculates the lateral spacing required for steady state subsurface drainage and subirrigation at the design rates using a modification of the steady state equation developed by Hooghoudt and by Ernst (van Beers, 1976) and formulated by Skaggs, 1978. The formulation includes an equivalent depth to the impermeable layer which is introduced to account for losses incurred as water flows outward during the subirrigation mode and for the losses that occur as the flow converges to the drain openings during subsurface drainage. Hooghoudt (van Schilfgaarde, 1974) evaluated that effect by comparing radial flow near the pipe with flow conforming to the Dupuit-Forchheimer assumuptions away from the pipe. Hooghoudt's solutions, formulated by Moody (1966), are used to iteratively calculate lateral spacings for the drainage and subirrigation modes using hydraulic conductivities, depth to barrier, depth to tile and depth to water table values provided by the user. Thus, the module computes two lateral spacings: one for subsurface drainage and the second for subirrigation. The design lateral spacing for the transient analysis is set to the lessor of spacing for drainage and subirrigation. The model user is given the option of choosing a different design lateral spacing for subsequent calculations.

Transient analysis

As the first step in the transient analysis, the model establishes the maximum flow capacity of a lateral pipe using Manning's equation and user defined values for pipe diameter and grade. Next, the rise in water table resulting from infiltration of the design rain event is calculated assuming initially the system is in the subirrigation mode with the water table at user defined depths, at and midway between laterals. The initial water content is assumed to be at 80% of the drained upper limit water content. The rain event infiltration is assumed to cause: 1) an instantaneous leveling of the water table at a depth equal to the average depth at the lateral and depth midway between laterals and 2) an instantaneous rise in the water table sufficient to store 100% of the infiltrated rain using the weighted, sat - .80 * dul, water content.

The modified Hooghoudt steady state equation is used to calculate the drainage flux. The energy head used is the difference between the depth to the pipe and the water table depth resulting from the rise in water table because of rain infiltration.

The water table drawdown time is calculated in two phases. For the first phase, the water table is assumed to vary from approximately horizontal to elliptical (see Figure 3). For the ellipse, 1/2 the ellipse vertical height is equal to the difference in the pipe depth and the water table depth immediately following the rise in the water table due to runoff distribution, at time = 0. The horizontal width of the ellipse is equal to the lateral spacing. The time for phase 1 is calculated by varying the horizontal width of the water table ellipse curve from 0 to one-half lateral spacing in 1000 steps, integrating the ellipse curve at each step and calculating the time to drain the volume of soil between steps. The time for drainage between steps is calculated by dividing the volume drained between steps (the area between steps times the difference in soil water content at saturation and soil water content at drained upper limit) by the average of the drainage flux between steps. The drainage flux at each step is calculated using the Hooghoudt equation as previously defined. The calculated drainage flux is not allowed to exceed full pipe capacity nor be less than the sum of the user defined drainage and subirrigation rates.

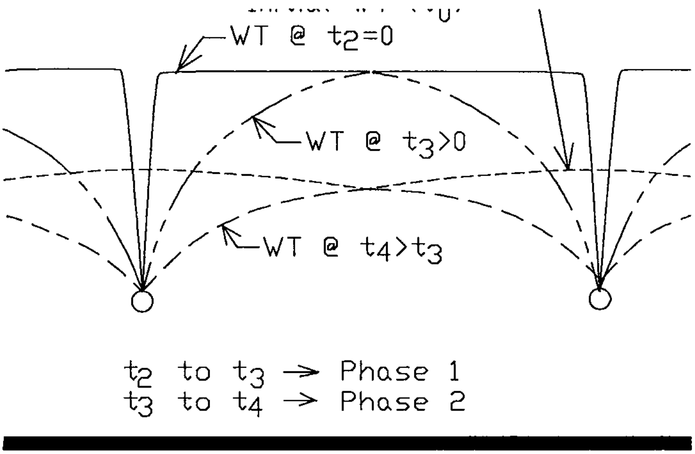

Figure 2. Schematic showing change in water table (WT) with time (t) following a rainfall event through water table drawdown with the system initially in a subirrigation mode.

For phase 2 flow, the elliptically shaped water table is dropped vertically in 30 mm midpoint increments from the midpoint height of the water table at the end of phase 1 to the midpoint depth of the water table in steady state subirrigation mode before the rainfall event. At each incremental drop, the curve is integrated and the time to drain the volume of soil within the increment is calculated. The time for drainage between increments is calculated by dividing the volume drained between increments by the average of the drainage flux between steps. The drainage flux at each increment is computed by the Hooghoudt equation as previously described.

During the phases 1 and 2 calculations, the time is accumulated and the elapsed time, water table depth at midpoint and drainage flux are displayed at each step.

Calculated crop yield parameters

The model uses the rise in water table, number of events and elapsed drawdown time to calculate a crop yield parameter called the wet stress fluctuation index (wfi). The wfi is a parameter that may be used to determine the probable mean crop yield that the subirrigation system described by the input data will produce. The wfi quantifies the fluctuation of water table above the mean over the period of time represented by the number of events defined by the program user. This provides a water table fluctuation parameter that can be used to estimate yield by comparing the computed wfi to previously determined wfi vs. yield relationships obtained through field studies and/or simulation models such as DRAINMOD.

The module calculation of wfi is based upon a rise and fall of the water table resulting from the user defined rainfall as shown by Figure 3.

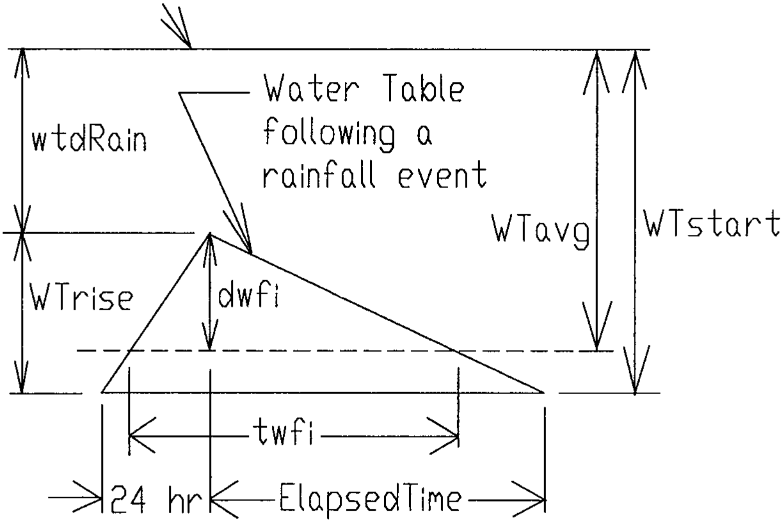

Figure 3. Schematic of assumed water table elevation vs. time folowing a rainfall event.

The wfi parameter is calculated by the following mathematical equation:

$$\mathrm{wfi} = \frac{\frac{1}{2}\ \mathrm{twfi\ dwfi\ events}}{\mathrm{totaltime}\ 24} \qquad (1)$$

where: events = number of rainfall events during the time period of interest, and

TotalTime = Duration of time period of interest (days).

$$\mathrm{dwfi} = \mathrm{WTavg} - \mathrm{wdtRain} \qquad (2)$$

$$\mathrm{twfi} = \frac{\mathrm{dwfi}\,(24 + \mathrm{ElapsedTime})}{\mathrm{WTrise}} \qquad (3)$$

$$\mathrm{WTrise} = \mathrm{WTstart\text{-}WtdRain} \qquad (4)$$

$$\mathrm{WTavg} = \frac{\mathrm{WTstart\ a}\ +\ (\mathrm{wtdRain}\ +\ \frac{2}{3}\ \mathrm{Wtrise})\ \mathrm{b}}{24\ \mathrm{TotalTime}} \qquad (5)$$

$$\mathrm{a} = 24\ \mathrm{Total\ Time} - (24 + \mathrm{ElapsedTime}) \qquad (6)$$

The wfi parameter is analogous to the SEW_{30} parameter (Wesseling, 1974 and Bouwer, 1974) as originally defined by Sieben (1964) to evaluate the effect of fluctuating water tables on cereal crop production. The module uses the wfi concept instead of SEW_{30} for two reasons. A meaningful value for SEW_{30} is not possible using a 50% probability rainfall event projected over the growing season. Also, the operational concept of subirrigation is to establish a constant water table at a depth that will provide the water needs of the plant. Under that situation, the plant will develop a root system as needed to utilize the ground water via capillarity from the water table. The wfi parameter provides a quantitative evaluation of how well the system maintains a constant water table. The wfi parameter can be determined from research data of water table depth or elevations with time as well as computer simulations that provide water table depth with time as an output. It has been shown that crop yield can be related to the wfi parameter (Belcher, 1989). It is expected those relationships are mostly independent of soil and climate (as is SEW_{30}). This allows system designers to apply the crop yield results from a few field studies and/or computer simulations to a broad range of soil and climatic conditions through application of the SI-DESIGN computer model.

LSPACE results

The following results are displayed:

- maximum lateral spacing for subirrigation
- maximum lateral spacing for subsurface drainage
- lateral spacing used for the transient analysis
- time to return to the subirrigation water table depth
- maximum discharge for drawdown
- wfi

LSPACE evaluation and discussion

The LSPACE module was evaluated by comparing simulated subirrigation drawdown durations with observed drawdown durations for selected rainfall events that occurred during the 1986 and 1987 growing seasons at the Bannister, Michigan research site and the 1987 and 1988 growing seasons at the St. Johns, Michigan research site. For each rainfall event, the differences in saturated and drained upper limit volumetric water contents (sat-dul) were calculated by dividing the observed rainfall by the observed vertical rise in the water table. The sat-dul values used are listed in Table 1. The runoff curve number was calculated by the USDA, Soil Conservation Service curve number method (USDA, Soil Conservation Service, 1972). For the Bannister site a curve number of 82 was used (Hydrologic Soil Group C with contoured row crops in good hydrologic condition). The St. Johns site curve number is 75 (Hydrologic Soil Group C with contoured row crops in good hydrologic condition).

YEAR	SITE	OBS WELL	RAIN mm	WT DEPTH @ START m	OBS. DEPTH AFTER RAIN m	OBS. SAT-DUL	OBS. TIME TO DRAW-DOWN hr	SIMUL. DEPTH AFTER RAIN m	SIMUL. TIME TO DRAW-DOWN hr
1986	Bannister	WA4M1	29	0.62	0.42	0.15	17	0.39	25
1986	Bannister	WB2M2	29	0.43	0.30	0.22	43	0.28	46
1986	Bannister	WC6M1	29	0.78	0.42	0.08	72	0.22	62
1986	Bannister	WE2M1	29	0.86	0.52	0.09	72	0.56	67
1986	Bannister	WG2M1	29	0.37	0.29	0.36	60	0.40	65
1987	Bannister	WC2M1	11	1.41	0.73	0.02	91	0.72	35
1987	Bannister	WE4M1	11	1.16	0.51	0.02	77	0.92	60
1987	Bannister	WE4M1	11	2.00	1.29	0.02	112	0.71	60
1987	Bannister	WH4M2	11	1.47	0.93	0.02	55	0.71	60
1987	St. Johns	WB4M2	24	0.92	0.65	0.09	31	0.65	41
1987	St. Johns	WB4M2	23	1.21	0.86	0.06	58	0.79	52
1987	St. Johns	WC4M1	24	0.99	0.71	0.09	36	0.71	40
1987	St. Johns	WC4M1	23	1.14	0.78	0.06	79	0.73	64

Table 1. Comparison of water table drawdown simulation results to field observation

The results of comparing the observed water table rise and drawdown with simulated rise and drawdown are presented in Table 1. The comparison of observed and simulated water table rise and water table drawdown shows that the LSPACE module does a reasonably good job of simulating actual field conditions for soils with loamy clay (Bannister site) and loamy sand (St. Johns site) textures.

MAIN

The MAIN module assists the system designer in determining the needed diameters of the submain and main collector pipes. The module uses a tabular format for data input and results. The user describes the system layout by appropriate input data. The user must also define the pipe diameters and grades. To compute collector pipe design parameters such as drainage coefficient, subirrigation rate, water table depth, pipe depth, etc., the module uses the Manning's equation as follows:

$$\mathrm{FullPipeQ} = \frac{1}{n}\left(\frac{\mathrm{TileArea}}{\mathrm{Tile\ Perimeter}}\right)^{\frac{2}{3}}\left(\frac{\mathrm{TileGrade}}{100}\right)^{\frac{1}{2}}\mathrm{TileArea} \qquad (8)$$

where:

FullPipeQ = full pipe flow discharge, L^3/t;
n = Manning's roughness coefficient;
TileArea = cross-sectional area of the pipe, L^2;
TilePerimeter = wetted perimeter of the pipe, L; and
Tile Grade = grade of the pipe (drainage mode) and hydraulic grade line (subirrigation mode),%.

An unique option of the MAIN module is to display the system layout graphically on screen. By selecting the DISPLAY option from the Commands Menu, a schematic diagram is displayed. This allows the user to visually assess if the system layout described by the input data accurately depicts the desired layout.

COST

The COST module is used to estimate the cost of the alternatives being investigated. The user may input pipe length quantities, number of water table control structures, etc. or use saved values from the MAIN module calculations.

ECON Module

A water table management system to optimize the economic efficiency of biomass production involve tradeoffs. Reducing pipe size and/or lateral spacing will reduce system cost but will also reduce the ability of the system operator to maintain the water at the desired depth. Rainfall events may increase plant stress due to excess soil water which may reduce biomass production. Likewise deficit soil water conditions with biomass production reductions may result from the system operation not keeping up with crop water needs.

To evaluate field crop versus water table depth and fluctuation relationships in economic terms, the economic analysis computer module (ECON) was developed. The module compares water table management system annual benefit to annual cost for alternative levels of subirrigation system capability. This method of evaluating alternatives is described by Riggs and West (1986) and Potter (1985).

The positive contributors to the net annual equivalent value of an alternative consist of yield multiplied by the market value minus the production cost of the crop. The negative contributors consist of the system installation cost, the system operation and maintenance cost and the salvage value of the system all converted to an annual cost using an interest rate equal to a minimum attractive rate of return. Parameters such as future costs of production, market value, inflation, tax benefit and/or cost, value of land, etc. are not included in the analysis. Estimation of these parameters are highly judgmental and their inclusion would complicate the analysis without improving the accuracy of the comparisons.

Input required for the economic analyses consist of yield, with system and without system, production costs and product prices, system installation cost (from the COST module), minimum attractive rate of return in percent, and the economic life of the system before replacement.

The benefit/cost ratio calculated by the module for each subirrigation system design alternatives are then evaluated, by the module user, to select the alternative with the largest benefit/cost ratio over 1.00. A benefit/cost ratio less than 1.00 indicates investment in subirrigation may not yield a profit.

CONCLUSIONS

SI-DESIGN does a reasonably good job of simulating the performance of a water table management system in the subirrigation mode using input data that is relatively easy to obtain. It includes options to assess the economic factors needed to evaluate the annual cost of a water table management system design alternative and the average annual increase in income estimated to result from the alternative.

With limited yield versus water table depth/fluctuation parameter data, the model provides the water table management system designer with a procedure needed to design water table management systems that optimize the economic efficiency of biomass production.

The model provides water table management system designers with the capability to design water table management systems that meet current standards for subsurface drainage, that provide irrigation water to the root zone at a rate consistent with the crop needs and that limit fluctuation of the water table within limits established by the system designer.

MODEL AVAILABILITY

A printed reference manual and computer diskettes containing the compiled model with examples of use is available from:

SI-DESIGN Program Development Group
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A. W. Farrall Hall
Michigan State University
East Lansing, Michigan, 48824-1323
USA

ACKNOWLEDGEMENT

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REGIONAL HYDROLOGICAL MODELLING OF IRRIGATION AND DRAINAGE SYSTEMS : CASE STUDY IN ARGENTINA

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ABSTRACT. A proper understanding of the interaction of irrigation and drainage canals with an aquifer system is necessary to improve performance of irrigation. A further complication is that this mechanism must be studied with a detail sufficient to identify operational guidelines for specific portions of an irrigation and drainage system. Numerical simulation models provide a useful support in this respect, since specific operational procedures of irrigation and drainage canals can be evaluated in this way. The objective of this paper is to demonstrate the use of the model SIMGRO in an irrigated area in the Province of Mendoza as a support to decision-making of water management aspects.

The regional hydrologic model SIMGRO simulates the water flow in the saturated zone, the unsaturated zone and the surface water. It takes into account the effects of irrigation and drainage systems and its impact on the evapotranspiration of the different land uses.

Irrigated by the Lower Tunuyán River, the selected study area was 27,500 ha. It was defined by means of a finite element network consisting of 443 nodes and the distance between nodes is of some 1000 metres.

The model was run for the 87/88, 88/89 and 89/90 agricultural seasons and measured data were compared with the data calculated by the model. In order to understand how each parameter affects the results of the model and the importance of their accurate measurement, sensitivity analyses were performed.

RESUME. Modelisation hydrologique régionale de systêmes d'arrosage et de drainage : cas d'étude en Argentine. *Pour améliorer le fonctionnemment des systèmes d'irrigation il faut une compréhension appropriée de l'interaction entre les canaux d' irrigation et de drainage et le système d'aquifères.*

Une plus grande difficulté réside dans le fait que ce mécanisme doit être étudié d'une façon suffisamment détaillée pour réussir à identifier des règles opérationnelles pour des secteurs spécifiques d'un système d'arrosage et de drainage.

A cet égard les modèles numériques représentent une aide convenable du moment que par ce chemin des procédés opérationnels spécifiques de canaux d'irrigation et de drainage peuvent être évalués.

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Ce travail a pour objectif de démontrer l'emploi du modèle SIMGRO dans une aire d'irrigation de Mendoza comme un outil pour la prise de décisions sur la gestion de l'eau.

Le modèle hydrologique régional SIMGRO, simule le flux de l'eau de la zone saturée, la zone non saturée et l'eau libre. Il tient compte des effects des systèmes d'irrigation et de drainage et de leurs répercussions sur la production des cultures.

L'aire d'étude choisie a été de 27.500 hectares, arrosée par la rivière Tunuyán Inférieure. Elle a été définie au moyen de 443 noeuds séparés entre eux par une distance d'á peu près 1000m.

Le modèle a été calé sur les cycles agricoles 87/88, 88/89 et 89/90, et les donnés mesurées ont été comparées avec les calculées par le modèle. Afin de comprendre comment chaque variable modifie les résultats du modèle, et l'importance de leur mesure précise, des analyses de sensibilité ont été réalisées.

Ce travail présente les résultats obtenus grâce au calage du modèle dans une aire de la rivière Tunuyán Inférieure. On trouve encore des différences entre les données calculées et les mesurées, qui pourraient diminuer si on avait une information topographique de meilleure qualité.

INTRODUCTION

Irrigated areas all over the world have been expanding at a sustained rate. In Argentina (INTA, 1986) there are 1,539,200 ha under irrigation, 60% of which lies in the central-western part of the country. Mendoza, with 358,500 ha having irrigation water rights, is the province with the largest irrigated area. Mendoza's five main rivers used for irrigation purposes are: the Mendoza, Tunuyán, Diamante, Atuel and Malargüe.

Water administration is in the hands of the General Irrigation Department (DGI), which is responsible for managing rivers, dams and the inflow into the primary irrigation canals. The irrigation network is managed by users associations.

At present, water is allocated on the basis of the area with irrigation water rights, but there are no precise figures of the actual cultivated area. This practice has led to over-irrigation and often to a gradual rising of water tables in wet years. The result is soil salinization, which brings about a decline in productivity and environmental deterioration. On the other hand, during periods of drought, the inadequate distribution of scarce water reduces the production potential and increases both aquifer exploitation and production costs.

In the last 10 years mathematical models have been developed that make it possible to simulate the hydrological system with reasonable ease and accuracy. The groundwater flow model SIMGRO (Querner & Van Bakel, 1988) used in this study simulates the flow of water in the saturated zone, the unsaturated zone and the surface water. Once calibrated, the model constitute an excellent tool for the integrated planning of irrigated oases and rational management of water resources. For instance the model will help to anticipate the effects that may be caused by changes in superficial and groundwater allocation. Use of the model is aided by remote sensing, which makes it possible to ascertain the cultivated area accurately.

DESCRIPTION OF THE MODEL SIMGRO

SIMGRO (Querner, 1988) simulates the water flow in the saturated zone, the unsaturated zone and the surface water (Fig. 1). It takes into account the effects of irrigation and its impact on the water requirements of different crops. The model is physically-based and can therefore be used in situations with changing hydrological conditions. The model has been devised in such a way that its accuracy does not demand too many input data or too much computer time.

The saturated zone has been modelled by means of the finite element method. The region is divided into a finite number of elements. Quasi three-dimensional flow is considered, which means horizontal flow in water-bearing layers and vertical flow in the less permeable ones. The groundwater levels and fluxes are calculated per nodal point. The unsaturated zone is modelled per land use by means of two reservoirs, one for the root zone and one for the subsoil (Fig. 1). The root zone is considered to have inflows and extractions, being: precipitation; evapotranspiration; irrigation; percolation and capillary rise. Water is stored in the root zone until equilibrium is reached. The excess water will percolate to the saturated zone. The groundwater level is calculated from the water balance of the subsoil, using a storage coefficient which is dependent on the depth of the groundwater level below soil surface.

The surface water system of a subregion, made up of a network of small canals, is modelled as a single reservoir per subregion taking into account water deliveries, irrigation water extractions, etc (Querner, 1993).

A subregion is made up of a number of nodes, where soil properties and hydrological conditions are homogeneous. Land use is divided into the following categories: agricultural areas, urban areas and nature reserves. Agricultural areas are irrigated with surface water and/or groundwater.

SELECTION OF THE STUDY AREA

The Lower Tunuyán River (Mendoza, Argentina) irrigates an area of some 90,000 ha with an important network of irrigation canals delivering water to 74,300 ha (Fig. 2). The irrigation water for this scheme is extracted from the Tunuyán River at the Gobernador Benegas diversion work. To guarantee water requirements a storage dam has been constructed upstream. The water flow is diverted to the Right Bank Main Canal or Reduccion Canal (13,000 ha) and to the Left Bank Main Canal (75,000 ha).

The original irrigation scheme has been constructed about sixty years ago. Primary canals are partially concrete lined (trapezoidal) and serve lower order canals. The secondary and tertiary canals are unlined. The irrigation scheme functions with continuous flow in the primary and secondary canals and with rotation delivery at tertiary level (Manzanera et al., 1992). The average area served by a tertiary canal ranges from 60 to 180 ha.

The Tunuyán River irrigation district is one of the most productive areas in the province, a large number of investigations have been carried out dealing with its irrigation and drainage network, soils and irrigation water use efficiency (both at network and farm levels). Also water delivery simulation and optimization models have been devised (Chambouleyron et al., 1982). Two of the consequences of poor irrigation water management practices in the study area have been soil salinization and rising water tables (Morábito et al., 1990).

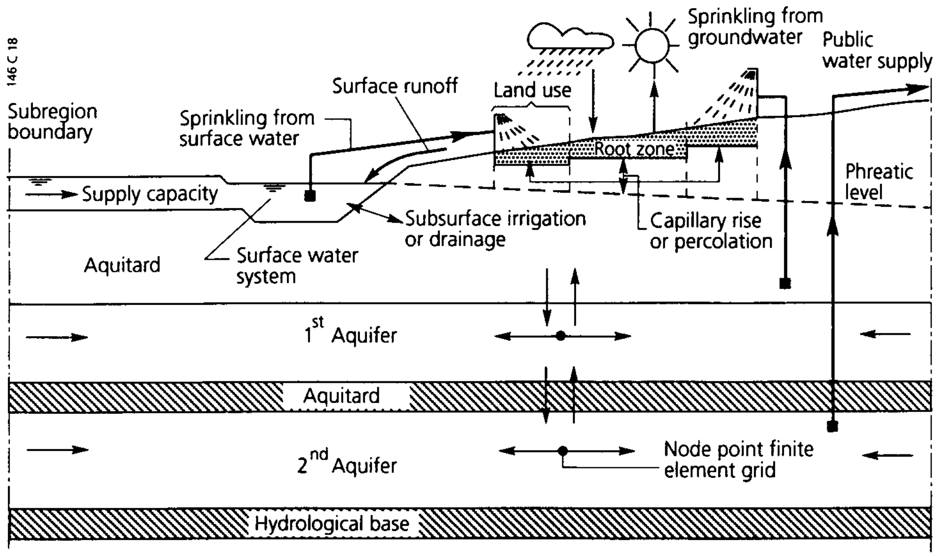

Figure 1. Schematization of the hydrological system in the model SIMGRO (Querner, 1988).

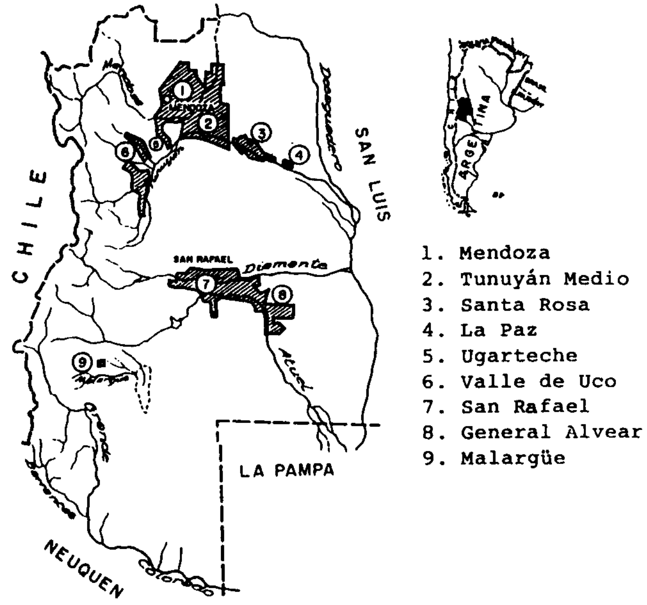

Figure 2. Irrigated areas in Mendoza, Argentina. Part of district 2 is taken as pilot area, receiving water from the Lower Tunuyán river.

As the command area of the Lower Tunuyán River is large and the financial resources for this study were limited, it was decided to select a portion, being 27,500 ha. This area lies between 640 and 715 m above MSL (Mean Sea Level). The soil is of alluvial origin and the predominant texture is loamy sand.

INPUT DATA FOR MODEL SIMGRO

Nodal network in the study area

The network, comprising 443 nodes spaced about 1000 m apart, is shown in Figure 3. The nodal network of the irrigation area was subdivided into 30 subregions, of which 6 are considered outside the actual pilot area. The subregions are identified by means of the following criteria:

1. Command area of the primary and secondary canals. This was taken into account because: a) water management in a canal affects its command area; b) water distribution is monitored at the intake of a canal and so it is possible to know how much water has been assigned; c) users associations manage the command area of primary and secondary canals.
2. Different soil types. When the command area of a canal is too large and there are differences in soil texture, it was divided into more subregions, one for each soil type.

For the groundwater system 5 layers were considered. The first, third and fifth layer are aquifers with transmissivities ranging between 2000 and 3200 $m^2 \cdot d^{-1}$. The second and fourth layer are aquitards having a vertical resistance of 500 and 200 days respectively.

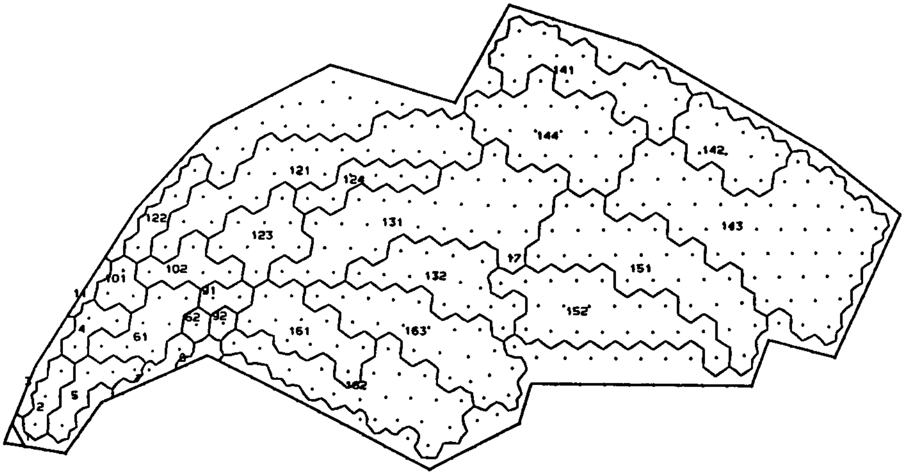

Figure 3. Finite element network of the study area and the division in subregions.

Determination of the cultivated area and cropping pattern

The actually cultivated area in the region was calculated by means of a 1986 satellite image (Zuluaga, et al., 1992). The cultivated area was divided into five different technologies: grapes (vineyard), grapes (trellis), fruit trees, vegetables and fodder. In addition to this, both the uncultivated and urban areas were considered (Table 1).

The percentages corresponding to each technology were obtained through field questionnaires conducted in representative sectors of each canal and supplemented with data from the 1988 National Agricultural Census (Estadisticas Agropecuarias, 1988). The urban areas in each subregion were determined with plane surveying (Table 1).

Subregion	Vineyard	Trellis	Fruit	Vegetables	Fodder	Uncultivated	Urban	Total area (ha)
4	22	27	0	0	0	51	0	216
5	21	25	11	0	0	43	0	347
61	20	18	23	4	0	35	0	615
62	11	14	11	4	0	60	0	106
91	2	2	1	0	0	95	0	39
92	5	5	11	1	0	78	0	100
101	23	25	7	4	2	38	1	230
102	17	36	7	4	2	22	1	485
121	43	28	7	2	2	15	3	2324
122	37	26	7	2	2	23	3	410
123	43	31	7	4	2	10	3	917
124	34	26	7	2	2	26	3	598
131	22	49	2	7	2	15	3	3034
132	22	30	2	4	2	37	3	1018
141	32	34	11	4	1	17	1	1645
142	32	37	11	4	1	15	0	1100
143	26	25	9	2	1	36	1	3960
144	32	34	11	4	2	7	10	2090
151	37	32	6	2	2	14	7	2593
152	33	23	6	2	2	19	15	1728
161	20	17	20	4	0	39	0	990
162	10	12	7	1	0	70	0	1568
163	20	12	24	4	0	39	1	1412

Table 1. Land use (%) for the study area derived from remote sensing, field questionnaires and the National Agricultural Census.

The model SIMGRO requires the potential evapotranspiration of a reference crop as input data. The potential evapotranspiration of each crop was derived using crop factors (Kc). These values were taken from local studies (Oriolani, 1981) and are given in Table 2.

Month	Grapes (vineyard)	Grapes (trellis)	Fruit trees	Vegetables	Fodder	Uncultivated
Aug	0.20	0.20	0.20	0.40	0.40	0.20
Sept	0.27	0.27	0.35	0.50	0.60	0.20
Oct	0.42	0.47	0.78	0.50	0.95	0.20
Nov	0.60	0.77	0.96	0.60	1.05	0.20
Dec	0.68	0.86	1.02	0.70	1.05	0.27
Jan	0.73	0.92	1.02	0.90	1.05	0.37
Feb	0.73	0.93	0.96	1.10	1.05	0.47
Mar	0.69	0.86	0.86	1.00	1.05	0.40
Apr	0.62	0.69	0.70	0.60	1.05	0.25
May	0.30	0.35	0.35	0.40	0.80	0.20
Jun	0.20	0.20	0.20	0.40	0.40	0.20
Jul	0.20	0.20	0.20	0.40	0.40	0.20

Table 2. Crop factors (Kc) used for the simulations with the model SIMGRO (Oriolani, 1981).

Estimation of applied irrigation water from surface and groundwater

For the calibration of the model it was necessary to have information on the water volumes entering the canal network. The volumes measured at the primary canal intake have been multiplied by a conveyance efficiency of 65% along the network (Chambouleyron et al., 1982). In order to transform these volumes into irrigation depths, the actually cultivated areas, calculated by remote sensing, were taken into account (Zuluaga et al., 1992). For the irrigation season 1988/89 the irrigation depths are given in Table 3.

Canal	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
1	10	132	128	153	158	188	135	136	88	84	86
2	9	90	86	106	120	122	83	77	50	51	46
3	0	92	100	120	121	141	132	130	80	74	78
4	0	52	62	78	84	27	74	65	43	44	48
5	0	45	54	70	77	25	69	59	40	45	41
6	0	44	80	95	94	30	92	83	54	56	61
7	8	69	73	89	94	109	82	81	58	62	55

Canals serving the subregions (Fig. 3):

1-	5, 62, 92, 162, 61, 91, 161, 163	5-	132
2-	102, 123	6-	151, 152
3-	121, 124, 141, 142, 143, 144	7-	4, 101, 122
4-	131		

Table 3. Estimated surface irrigation water depth (mm) used in the model SIMGRO for the irrigation season 1988/89.

The calculated volumes of extracted groundwater in the study area during 1987-1990 irrigation seasons were obtained from Pazos (1991). For this purpose the study area has been divided into five sectors corresponding to the five companies that provide the electricity required to operate the pumps. The extracted amounts of groundwater and applied for irrigation is given for the irrigation season 1988/89 in Table 4.

Sector	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
I	15	10	8	12	5	3	22	20	22	12	6
II	39	21	11	18	6	4	56	43	31	19	8
III	26	7	4	6	5	4	38	15	11	6	6
IV	30	10	5	5	5	5	45	20	11	5	5
V	46	27	25	27	15	12	60	50	64	26	17

Sector includes subregions (Fig. 3):

I- 141, 142, 143, 144
II- 131, 132, 151, 152
III- 5, 61, 62, 91, 92, 161, 162, 163
IV- 4, 101, 102
V- 121, 122, 123, 124

Table 4 . Estimated irrigation from groundwater (mm) for the irrigation season 1988/89.

RESULTS OF SIMULATIONS WITH SIMGRO

Model calibration

In order to calibrate the model it was run for the 87/88, 88/89 and 89/90 agricultural seasons. Figure 4 shows the calculated and measured groundwater levels for nodes 131 and 191 for the 1987/88 period. A problem faced by the comparison is the fact that the observed groundwater level is for a certain location, whereas the calculated level is an average for the area associated with a nodal point (see Fig. 3). The calculated level remains parallel to the measured level throughout the season, with a slight upward or downward shift. This shift may be contributed to the difference in ground level between the nodal point and the observation well.

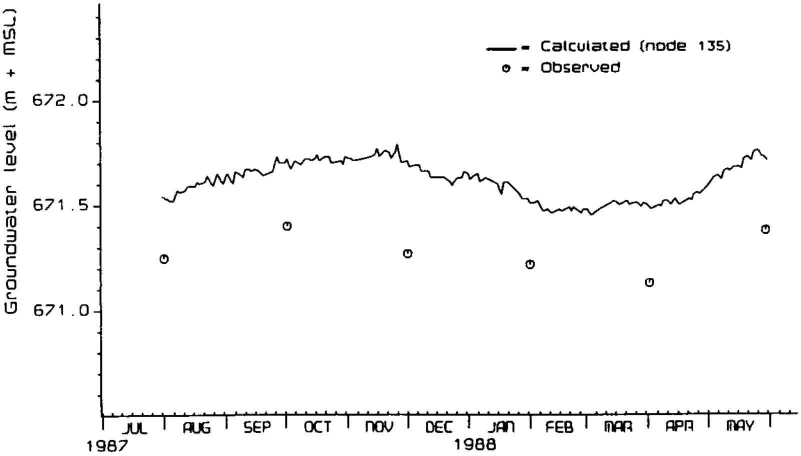

Figure 4. Comparison of simulated and measured phreatic groundwater levels.

An analysis was made of the standard deviations between calculated and measured data of 15 nodes for the three agricultural seasons and the results yielded an average deviation (root mean square) of 0.663 m (87/88), 0.639 m (88/89) and 0.488 m (89/90), respectively.

Another parameter considered for comparison was evapotranspiration. Figure 5 shows optimum water requirement values (potential evapotranspiration, according to FAO) given on a monthly basis for two crops: a) peaches (variety Palora cling) grown at INTA Junín Experimental Station (1959-68); and b) grapes (cultivar Cherry) grown at INTA Luján de Cuyo Experimental Station (1973-81). Also shown are actual evapotranspiration data for subregion 123 calculated by the model SIMGRO. Actual evapotranspiration calculated by the model is for peaches about 80% and for grapes about 87% of the potential evapotranspiration, which correlates with the less than potential production observed in this area.

The model makes it possible to calculate irrigation efficiency in the study area. Project efficiency (ep) has been defined as the ratio between the actual evapotranspiration and the total volume of water used for irrigation (surface and groundwater). Figure 6 shows ep variations throughout the year for the three agricultural seasons under consideration. The results yield an average of 42.5%, which is very close to the measured value of 39% (Chambouleyron et al., 1982).

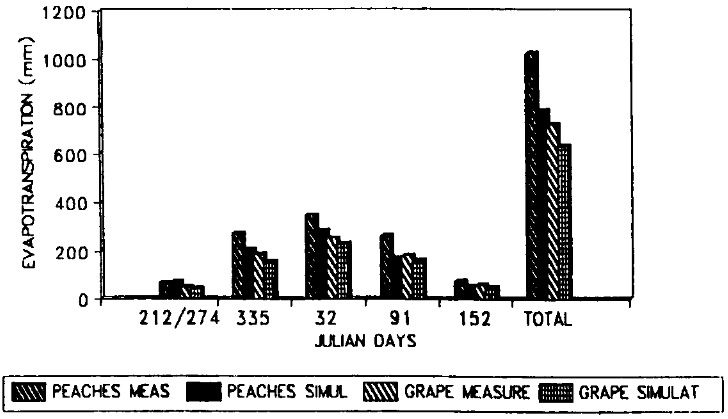

Figure 5. Comparison of simulated evapotranspiration for subregion 123 and compared with the potential values according to FAO (1977).

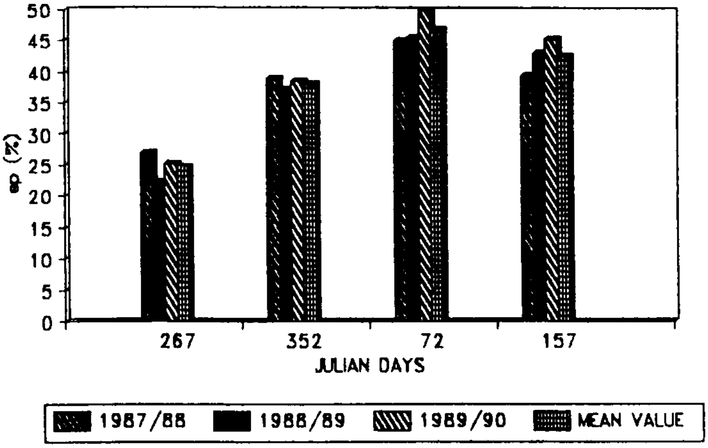

Figure 6. Yearly evolution of project efficiency (ep is ratio actual evapotranspiration and the total volume of irrigated water from surface water and groundwater).

Sensitivity analysis

Before the model can be used with confidence in situations with less observed data, it has to be proved that the input data do not impose an undue problem. Specifically the uncertainty in the values need to be analysed. This qualitative assessment of the input data was carried out in the form of a sensitivity analysis. A single parameter was varied each time from its best known value, either measured in the field or taken from the literature. The effects on groundwater levels were assessed by the mean standard deviation.

The parameters analysed were the following: entry resistance of irrigation canals, vertical resistance, storage coefficient, aquifer transmissivity, crop coefficient, amount of surface and groundwater applied, and cultivated area. A ranking of the sensitivity of the parameters was established and they were divided into three different groups:

1) Variables which affected the results, being: amount of surface water applied for irrigation, transmissivity and cultivated area;
2) Variables which affected the results to a lesser extent, being: crop coefficient, entry resistance of irrigation canals and vertical resistance;
3) Variables which had little effect on the results, being: amount of groundwater applied for irrigation and storage coefficient.

CONCLUSIONS

The benefits of a physically-based model, such as SIMGRO, is the use in situations with changing conditions having an affect on the hydrological system. An important aspect when developing such a model for irrigation practice is the need to simulate the hydrological processes as accurately as possible and to include operational irrigation practice. The draw back of such a modelling approach is the great demand on reliable input data.

This paper sets forth the results obtained through the calibration of the model SIMGRO in an area irrigated by the Lower Tunuyán River. There still exist differences between the measured and the calculated data, but the model is able to reproduce water table variations with acceptable levels of accuracy. The model is suitable as a planning tool for water use in irrigation schemes.

The modelling approach described in this paper focused on the effects of irrigation on the groundwater system. Described elsewhere (Manzanera et al., 1992) is the modelling approach of the water flow in irrigation canals. Both groundwater and surface water models will be integrated to obtain one model for the hydrological system of irrigation systems.

This paper also demonstrates that the model is very effective to establish which parameters require more accurate measurement. From the analysis of each of the variables, sound management principles may be developed that can be applied at the present time and as the situation evolves. They will, in turn, lead to a better water use and increased production.

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Additional Paper

Article supplémentaire

THE COMPUTER PROGRAM SALBAL

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ABSTRACT. Salinity control is essential to sustained irrigated agriculture. Salinity control in arid conditions is realized by leaching with irrigation losses or special water applications. The applications for leaching only should be minimal and preferably scheduled in off-periods, because water is progressively becoming a scarce and valuable resource, and agriculture has to compete with other sectors for its use. SALBAL is a computer program that permits a quick evaluation of the risk for salinization of cropped soil in relation to irrigation regime, climatic conditions, salinity of irrigation and groundwater, and crop sequence. The program is based on the analysis of the distribution and transport of water and salt in the soil in relation to soil conditions, irrigation, rainfall, capillary supplies and moisture used by plants for evapotranspiration. The soil profile is divided into layers and the time in calculation periods. The number of soil layers is not limited by the program, and the length of periods may be varied per entry. This permits to cover by one entry an off-season period of several months, in which the soil profile is completely desiccated, or re-salinization via capillary rise of saline groundwater is simulated. The model calculates the equilibrium soil salinity conditions which are reached if the selected crop and irrigation schedule is continued for a long period. The results of the calculations are presented in tables or graphs showing the moisture and salt distribution in the different soil layers at their end of the periods considered. The model can be calibrated by introducing a leaching efficiency coefficient and the selection of the thickness of soil layers.

SUMMARY (to be translated in french). Even the best quality irrigation water contains some dissolved salts, and crops are selective in their ion uptake; consequently some salts will accumulate in the root zone if only the water needed for evapotranspiration is supplied. The control of salinity in the root zone is essential to sustained irrigated farming in arid conditions. Therefore the deposited salts have to be leached to the sub-soil by excess irrigation water.

There are two good reasons to limit this leaching to the minimum required for salinity control:

- Irrigation water is a scarce resource, so it should not be wasted.
- The leached water will eventually cause a rise of the groundwater level, necessitating drainage measures. Minimum supplies for leaching results in minimum requirements for drainage.

The actual chemical/physical processes that cause the salt accumulation in the soil profile are rather complicated, and consequently computer simulations that try to describe the dynamic processes in full detail are very elaborate and unwieldy to the users.

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SALBAL is an interactive approximative model. It calculates the equilibrium soil salinity resulting from the irrigation regime, water quality, climatic conditions and cropping pattern as specified by the user. SALBAL is an in-house development of Euroconsult, originally developed and written in 1984 by Boumans, transcribed in QBasic, updated and improved in later years by Van Achthoven and others. The program is a follow-up of earlier salt simulation models for manual calculation, published by Boumans in 1963 (ILRI 1977) and Van der Molen in 1973 (ILRI 1977).

This article describes the inputs and outputs of the program and recapitulates the theory used for the model. The model can be calibrated by a variable efficiency coefficient. SALBAL calculates the final equilibrium levels of salt in the soil profile which are reached after a number of growing cycles of the chosen crop sequence, irrigation schedule and climatic data. The input and output procedures of SALBAL are illustrated in Appendix 2 with a demonstration example for one year wheat/fallow rotation with irrigation rainfall and capillary supplies.

The example shows the relative ease of preparing the inputs compared to other dynamic models where daily input data are required. The use of suitable longer periods speeds up operations dramatically.

The ease of entering and changing data permits to make several trial runs with varying amounts of excess irrigation water for leaching. The program option for graphical display of the resulting soil salinity at the various depths in the soil profile is very helpful while interpreting the results.

INTRODUCTION

Even the best quality irrigation water contains some dissolved salts, and crops are selective in their ion uptake, consequently some salts will accumulate in the root zone if only the water needed for evapotranspiration would be supplied. The control of salinity in the root zone is essential to sustained irrigation farming in arid conditions. Therefore the deposited salts may have to be leached to the sub-soil by excess irrigation water.

There are two good reasons to limit this leaching to the minimum required for salinity control:

- Irrigation water is a scarce resource, so it should not be wasted.
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The actual chemical/physical processes that cause the salt accumulation in the soil profile are rather complicated, and consequently computer simulations that try to describe in all detail the dynamic processes are very elaborate and makes them unwieldy to the users.

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PROGRAM DESCRIPTION

Input data

By means of input screens the user is requested to supply the following input data regarding soil, crop, irrigation and climate.

- Depth of the soil profile in cm.
  The depth, larger then the rooting depth, where below the moisture content may be assumed to be constant during the studied period. Depths of 120 cm for field crops and 150 cm for tree crops are in general sufficient.

- Number of equally thick layers.
  The choice of the number of layers determines the thickness of soil elements for the calculation of the moisture and salt regime. Variation of thickness may a way to calibrate the model. Sufficient accurate results are obtained with layers between 15 and 25 cm thick. Boundaries of soil strata with different textures should be taken into account (different moisture storage capacity).

- Moisture content at field capacity.
  The field capacity of each soil layer, depending on type and texture, is to be entered in % by volume .

- Number of periods.
  The number of logical calculation periods in which the growing cycle includes fallow periods is to be divided. The periods may have variable length and should theoretically correspond to irrigation intervals. For practical reasons the growing cycle is often divided into periods of 1 or more calendar months. The length of the growing cycle should cover at least one full year.
- Leaching efficiency.
  A part of the water draining from a soil layer has passed through cracks and holes and is not effective for the leaching of salts. The leaching efficiency coefficient is defined as the fraction of the total drainage efficiency for leaching. The leaching efficiency is smallest at the surface, and will be 1 where the soil is permanently saturated. The program asks for two entries:

  (1) The efficiency at 50 cm depth. Sample values are: 4 for clay till 8 for loamy sand, both for gravity irrigation of non rice crops. Rice crops and sprinkler irrigation have higher values. (2) The depth where the efficiency becomes 1. common values are 100 to 150 cm.

  The program calculates efficiency values for the different soil layers through linear interpolation but with a minimum value of 0.1. The choice of the efficiency value is a means to calibrate the model.

- Salinity of capillary supply.
  Groundwater may enter the soil profile from below by capillary flow. The salinity of the capillary supply may be equal to the average salinity of the water draining from the profile, which is the common case, or different. The second case occurs for instance when the profile is underlain by an aquifer with a salt regime not, or only partly, related to the salinity of the overlying soil.

- Salinity of the rain water.
  Should not be neglected in coastal areas.

- Irrigation and capillary supply.
  For each period the irrigation depth or estimated capillary supply can be entered. Periods with capillary supply should be different from those with irrigation.
  Irrigation and rain replenish the soil layers starting from the top to field capacity. Excess water drains down to deeper layers. The capillary rise is distributed over the soil layers.

- Precipitation per period.
  The model assumes that rain occurs at the start of a period. So the selection of periods should take into account the occurrence of heavy showers.

- Salinity of irrigation water per period.
  The model assumes that salts remain in solution during their stay and transport in the soil. If the irrigation water contains not negligible quantities of low soluble salts (carbonates and gypsum), the input salinities as well as the resulting salt data have to be adapted.

- Rooting depth per period.
  The rooting depth must not exceed the profile depth. For fallow periods enter the depth of the roots of the weed vegetation.
  If 0 is entered, it is assumed that evapotranspiration takes place from the first layer only.

- Evapotranspiration per period.
  Enter calculated or estimated values per period. Also enter values for the fallow periods. The model assumes that evapotranspiration is extracted from the rootbzone as follows: 40% top quarter, 30% second quarter, 20% third quarter, 10 % bottom quarter. The program gives a warning if entered evapotranspiration exceeds the available moisture in the root zone, which is set at 55% of the moisture content at field capacity.

- Control of input data.
  The total water balance should be positive, i.e. the sum of irrigation, precipitation and capillary rise over the growing cycle studies, must be larger than the total evapo-transpiration over that period. If not, no leaching occurs and no equilibrium salt level in the soil can be reached. In that case the program will ask to adjust the input data.
  Also per period the water balance should match. The program will halt and ask for adjustment if evapotranspiration exceeds the total moisture in the root zone.

Data processing

The salt movement can be calculated only after the water balance of the considered period has been calculated. Therefore the modelling of the salinity regime of an irrigated soil consists of two successive steps. First the water balance is analysed, then the corresponding movements of salt are calculated.

The water balance

The program calculates the soil moisture balance by trial and error in a way that moisture content and distribution at the end of the cropping cycle are the same as those at the beginning of the cycle studied.

The layers will be replenished, starting from the top layer, by irrigation supply or precipitation, up to field capacity, after which the excess water percolates further down.
During the non-irrigation (fallow) period there may be a capillary rise (quantified by the user) from the groundwater below the specified bottom soil layer (indicated as negative irrigation). Irrigation and capillary rise cannot occur in the same period. It is assumed that capillary inflow is distributed over the root zone.

The moisture content of a soil layer at the end of the period depends on the moisture content at the end of the previous period, the desiccation through evapotranspiration, water supply by drainage from the next higher layer and by capillary rise and percolation (drainage) losses to the layer below, during the period. As already mentioned the calculation periods are selected such that irrigation hence also drainage occurs at the start of the period.

The basic relation (all quantities in mm water depth) is:

$$MC(p,n) = MC(p-1,n)+DR(p,n-1)+CI(p,n)-DR(p,n)-EV(p,n),$$

Where:

MC(p,n) = moisture content of layer n at the end of period p
MC(p-1,n) = same for previous period
DR(p,n-1) = inflow of water draining from the layer above. For the top layer n=1. The inflow
DR(p,n-1) = equals the supply from irrigation and precipitation .
CI(p,n) = possible contribution of capillary rise in fallow periods, see input data.
DR(p,n) = outflow of water draining the layer below. Drainage occurs after the moisture content has reached field capacity.
EV(p,n) = contribution of layer n to the total evapotranspiration in period p. Below the root zone EV=0

The salt balance

The salt supply to the soil originates from irrigation, capillary rise and sometimes also from rain. The salts move through the soil profile by percolation of salty water draining from one layer to the layer below. Water inflow from above is mixed with the water in the layer whereafter excess mixed water drains to the layer below. Salts are finally removed from the profile by the drainage from the bottom layer to the subsoil, but salts may reenter by capillary rise.

The simulation model for the displacement and distribution of salts in the soil profile during the cultivation cycle is based on the following relationships.

The program determines the equilibrium salt balance which is reached if the studied cropping cycle is continued for a long period. It implies that the salt content at the end of the calculation cycle is the same as that at the start.

SI(p,n) = SO(p,n-1)-SO(p.n) and
SO(p,n) = LE(n)*DR(p.n)*ECAfc(P,n)+{1-LE(n)}*DR(p.m)*ECi where:
SI(p,n) = increase of salt in layer n in period p mm*mS/cm (negative value for decrease)
SO(p,n-l) = incoming salt in period p with the water draining from the layer above in mm*mS/cm

SO(p,n)	=	outgoing salt in period p with water draining to layer below in mm*S/cm
LE(n)	=	leaching efficiency coefficient for layer n, demensionless
DR(pn)	=	water draining from layer n to layer n+l in period p, in mm
ECAfc(p,n)	=	EC of the soil solution at field capacity in layer n: average value of EC at the beginning and end of period p, in mS/cm.
ECi	=	EC of irrigation and/or rain water entering from the surface in mS/cm.

The output

The output of the program displays, apart from a listing of all input data, the results of the water and salt balance modelling as follows.

For each period and each soil layer are given in table form:

- The moisture content at the end of the period in terms of the moisture deficit in % below field capacity.
- The electrical conductivity, EC, of the soil moisture at field capacity at the end of the period
- The corresponding ECe, or EC of the saturation extract.
- The percolation of water to the layer below (drainage, leaching).

Further for each of the periods the average salinity of the root zone as the EC value of the soil moisture at field capacity and the corresponding ECe.

The salt balance results are also displayed in graphs showing the salinity of the different soil layers and of the root zone for the different periods of the cultivation cycle.

OPERATION OF THE PROGRAM

The program is completely menu controlled to make it as user friendly as possible in view of the rather complex nature of the calculation model. All input and output data are stored in separate files for further use. Submenu's permit to add or change data, or to select another section of output. The menu screens and the procedures to work with a previously entered file are shown in Appendix 1.

In Appendix 2 the inputs and outputs are shown for a demonstration run. For practical reasons a fictions short one year cycle of winter wheat and grazed summer fallow is analysed. The year is divided into 7 periods, five monthly irrigated periods for wheat cropping and two fallow periods of 2 and 5 months respectively.

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APPENDIX 1 - THE SALBAL SCREENS

Main menu

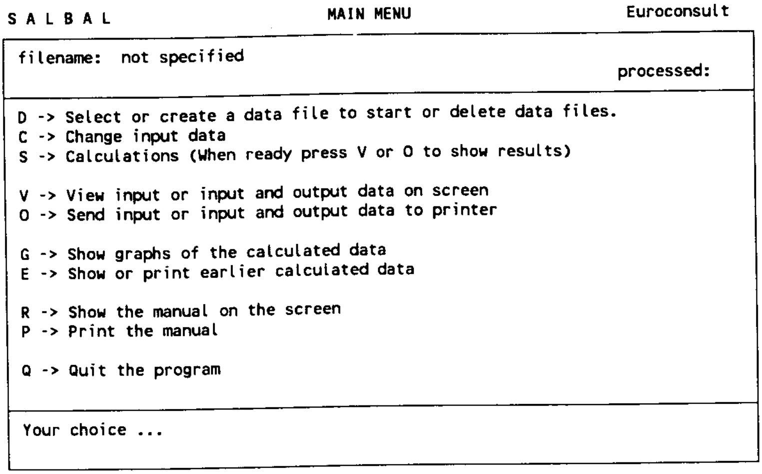
After the opening screens appears the main menu (Figure 1), placed centrally in the program: Each manipulation is initiated here, and one is returned here after completion of the job. To assist in keeping track of your actions a tack is placed in front of each completed action, this does not mean that this option is closed for another run.

Initially one must start with 'D' for opening a new file or calling an existing file for further processing.

"select a Data file to start operations, or delete files."

In this option one may create a new file, or as shown in the example below, choose an existing file for further processing.

The further options allow to change data, to perform the calculations, and to view or print the results.

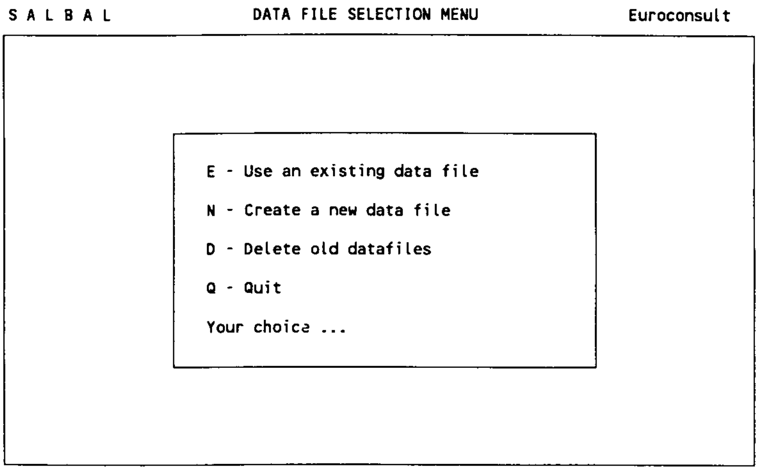


```
S A L B A L                    MAIN MENU                    Euroconsult

filename:  not specified
                                                      processed:

D -> Select or create a data file to start or delete data files.
C -> Change input data
S -> Calculations (When ready press V or O to show results)

V -> View input or input and output data on screen
O -> Send input or input and output data to printer

G -> Show graphs of the calculated data
E -> Show or print earlier calculated data

R -> Show the manual on the screen
P -> Print the manual

Q -> Quit the program

Your choice ...
```

Figure 1. The SALBAL Main Menu Screen

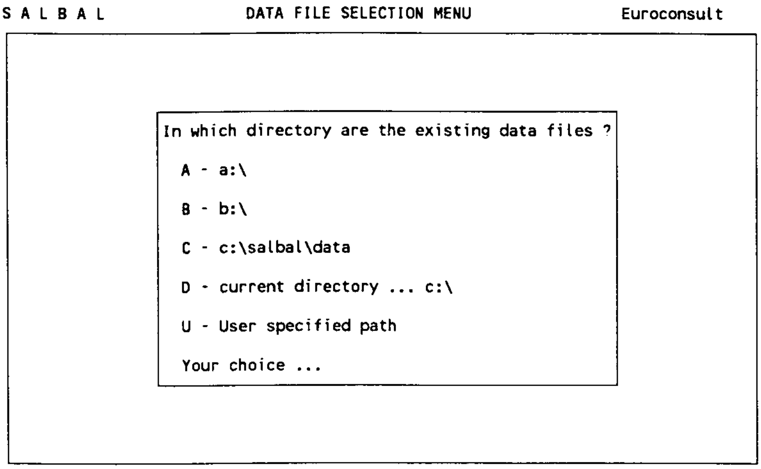
The submenus

The submenus of the SALBAl program are shown in Figures 2 to 12.



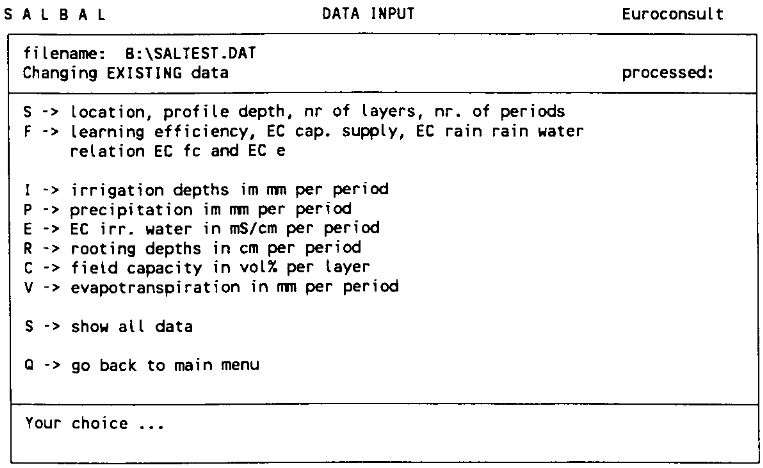
```
S A L B A L              DATA FILE SELECTION MENU              Euroconsult

                E - Use an existing data file

                N - Create a new data file

                D - Delete old datafiles

                Q - Quit

                Your choice ...
```

Figure 2. The SALBAL Data File Selection screen



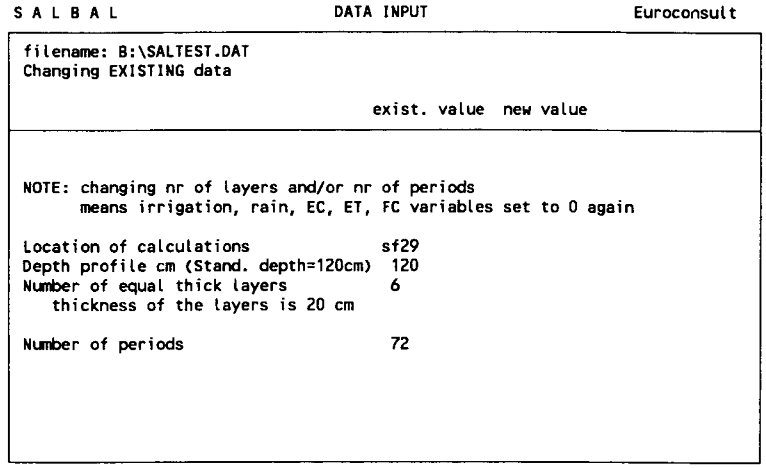
```
S A L B A L              DATA FILE SELECTION MENU              Euroconsult

             In which directory are the existing data files ?

               A - a:\

               B - b:\

               C - c:\salbal\data

               D - current directory ... c:\

               U - User specified path

               Your choice ...
```

Figure 3. Screen for selecting an existing data file



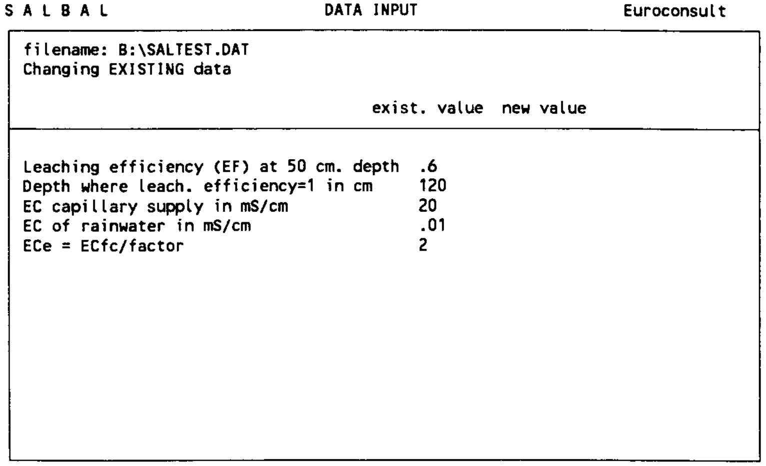
```
S A L B A L                      DATA INPUT                    Euroconsult

 filename:  B:\SALTEST.DAT
 Changing EXISTING data                                       processed:

 S -> location, profile depth, nr of layers, nr. of periods
 F -> learning efficiency, EC cap. supply, EC rain rain water
      relation EC fc and EC e

 I -> irrigation depths im mm per period
 P -> precipitation im mm per period
 E -> EC irr. water in mS/cm per period
 R -> rooting depths in cm per period
 C -> field capacity in vol% per layer
 V -> evapotranspiration in mm per period

 S -> show all data

 Q -> go back to main menu

 Your choice ...
```

Figure 4. The data input menu



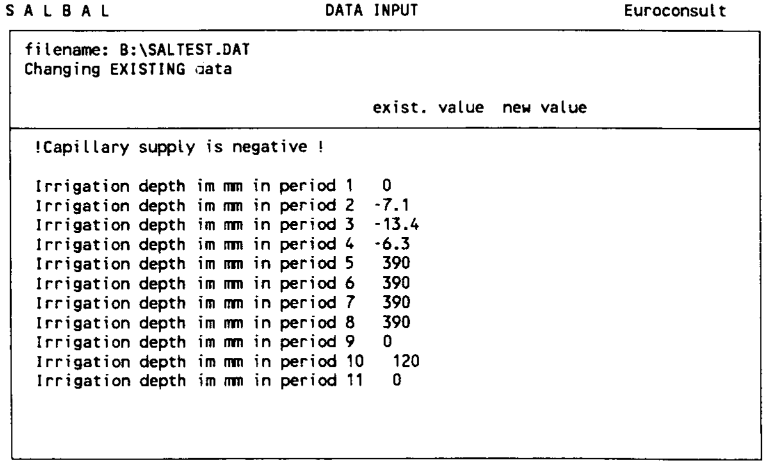
```
S A L B A L                         DATA INPUT                     Euroconsult

 filename: B:\SALTEST.DAT
 Changing EXISTING data

                                   exist. value  new value

 NOTE: changing nr of layers and/or nr of periods
       means irrigation, rain, EC, ET, FC variables set to 0 again

 Location of calculations              sf29
 Depth profile cm (Stand. depth=120cm)  120
 Number of equal thick layers           6
    thickness of the layers is 20 cm

 Number of periods                      72
```

Figure 5. The data input screen for location, profile depths, number of layers and number of periods.



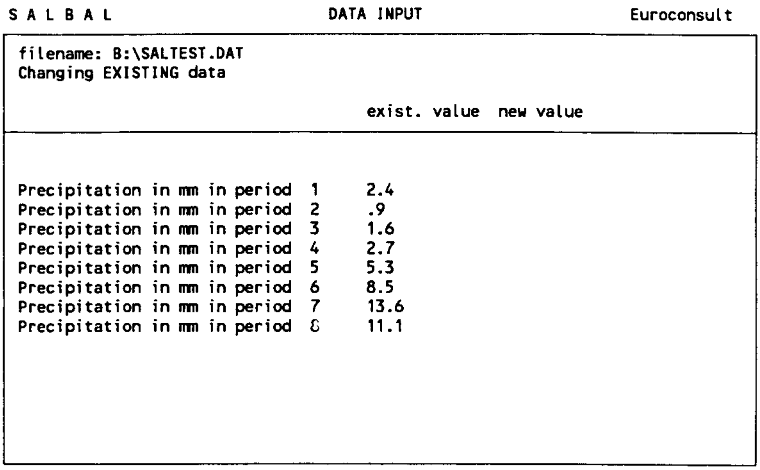
```
S A L B A L                         DATA INPUT                     Euroconsult

 filename: B:\SALTEST.DAT
 Changing EXISTING data

                                   exist. value  new value

 Leaching efficiency (EF) at 50 cm. depth  .6
 Depth where leach. efficiency=1 in cm     120
 EC capillary supply in mS/cm              20
 EC of rainwater in mS/cm                  .01
 ECe = ECfc/factor                         2
```

Figure 6. The data input screen for leaching efficiency and salinity of capillary supply and rain water



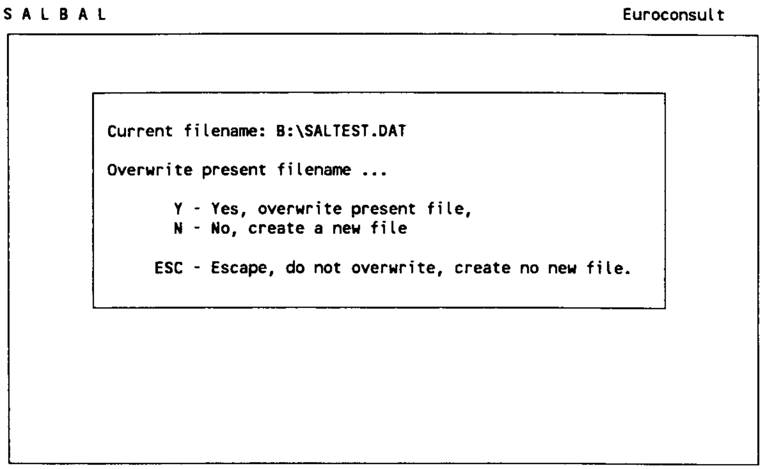
```
S A L B A L                         DATA INPUT                     Euroconsult

 filename: B:\SALTEST.DAT
 Changing EXISTING data

                                   exist. value  new value
  !Capillary supply is negative !

  Irrigation depth im mm in period 1   0
  Irrigation depth im mm in period 2  -7.1
  Irrigation depth im mm in period 3  -13.4
  Irrigation depth im mm in period 4  -6.3
  Irrigation depth im mm in period 5   390
  Irrigation depth im mm in period 6   390
  Irrigation depth im mm in period 7   390
  Irrigation depth im mm in period 8   390
  Irrigation depth im mm in period 9   0
  Irrigation depth im mm in period 10   120
  Irrigation depth im mm in period 11   0
```

Figure 7. The data input screen for irrigation depths supplies.



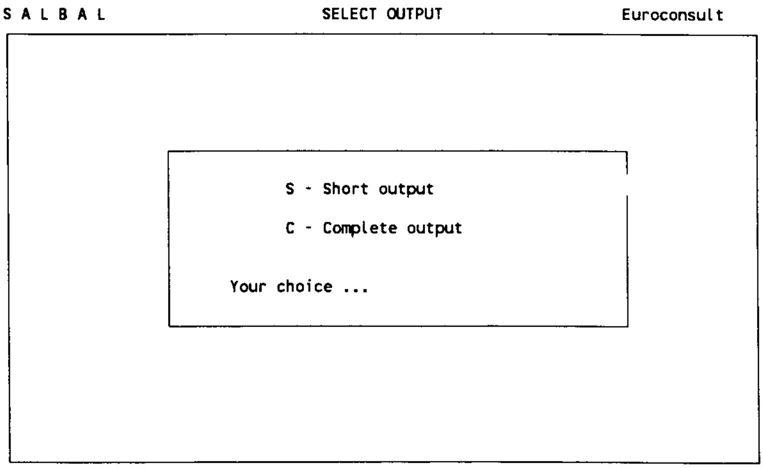
```
S A L B A L                    DATA INPUT                  Euroconsult

 filename: B:\SALTEST.DAT
 Changing EXISTING data

                                      exist. value  new value


 Precipitation in mm in period  1     2.4
 Precipitation in mm in period  2     .9
 Precipitation in mm in period  3     1.6
 Precipitation in mm in period  4     2.7
 Precipitation in mm in period  5     5.3
 Precipitation in mm in period  6     8.5
 Precipitation in mm in period  7     13.6
 Precipitation in mm in period  8     11.1
```

Figure 8. The data input screen for precipitation



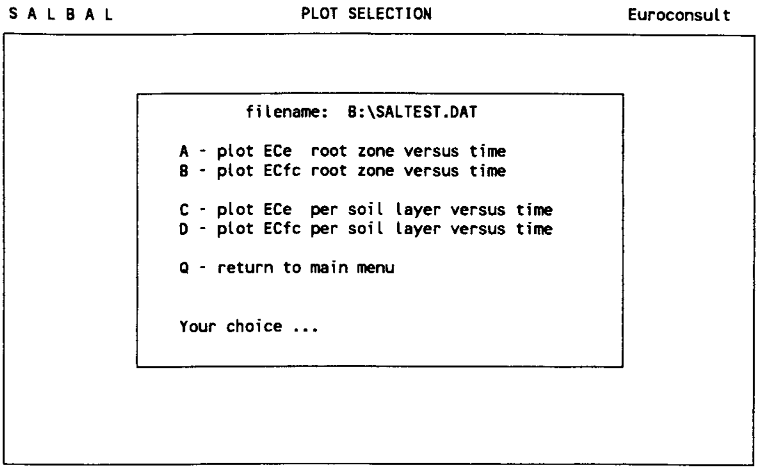
```
S A L B A L                                                Euroconsult

          Current filename: B:\SALTEST.DAT

          Overwrite present filename ...

                 Y - Yes, overwrite present file,
                 N - No, create a new file

               ESC - Escape, do not overwrite, create no new file.
```

Figure 9. Screen for saving newly created or changed data.



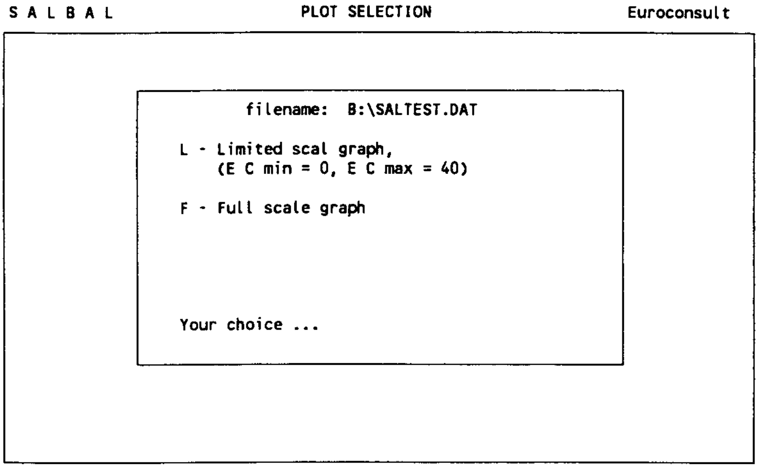
```
S A L B A L                  SELECT OUTPUT                 Euroconsult

                       S - Short output

                       C - Complete output


                 Your choice ...
```

Figure 10. Options for SALBAL output



```
S A L B A L                   PLOT SELECTION                   Euroconsult

            filename:  B:\SALTEST.DAT

       A - plot ECe  root zone versus time
       B - plot ECfc root zone versus time

       C - plot ECe  per soil layer versus time
       D - plot ECfc per soil layer versus time

       Q - return to main menu


       Your choice ...
```

Figure 11. Plot selection menu, graphical presentation



```
S A L B A L                   PLOT SELECTION                   Euroconsult

            filename:  B:\SALTEST.DAT

       L - Limited scal graph,
           (E C min = 0, E C max = 40)

       F - Full scale graph




       Your choice ...
```

Figure 12. Plot selection menu for the scale of the graphs

APPENDIX 2 - DEMONSTRATION RUN

A demonstration of the inputs and outputs of the SALBAL program is given below. For practical reasons a fictive short one year cycle of winter wheat and grazed summer fallow is analyzed. The year is divided in 7 periods. Five monthly irrigated periods for wheat cropping and two fallow periods of 2 and 5 months respectively.

The example shows the relative ease of preparing the inputs compared to other dynamic models where daily input data are required.

The ease of entering and changing data permits to make several trial runs with varying amounts of excess irrigation water for leaching.

```
SALT BALANCE CALCULATIONS      for file   a:\iciddemo.dat
==========================================================================
INPUT  DATA                                     04-21-1993
==========================================================================
for area : wheat/fallow     profile depth  110   cm

nr. of layers   :  4        thickness of layer :  27   cm
nr. of periods  :  7

leaching efficiency is   .6  at  50   cm depth
leaching efficiency is    1  at 100   cm depth

EC of capillary supply : av. EC of groundwater
EC of rain water       :    .05  in mS/cm
ECe = ECfc/ 2

period         irrigation    rain fall     EC irr water  root depth    evapotr.
               (mm)          (mm)          (mS/cm)       (cm)          (mm)
 1              120           25            .5            30            15
 2              100           46            .6            50            80
 3              70            45            .7            70            120
 4              70            60            .9            80            135
 5              100           10            1             90            80
 6              -80           25            1             70            95
 7              -60           45            .7            50            110
==========================================================================
TOTAL           320           256                                       635

layer          moisture content
               at field capacity
               (vol%)
 1              35
 2              35
 3              35
 4              35
==========================================================================
  CALCULATED DATA
==========================================================================

Intermediate calculated data

GROUNDWATER BALANCE FOR THE WHOLE PERIOD
==========================================================================

SUM Irrigations                (mm)        460
SUM Precipitation              (mm)        256
SUM Evapotranspiration         (mm)        635
SUM Capillary supply           (mm)        140
SUM Drainage water             (mm)        221
Average EC groundwater      (mS/cm)        4.2
Average EC capillary water  (mS/cm)        4.2

==========================================================================
```

RESULTS SALT BALANCE CALCULATIONS

FC is field capacity   EC is electrical conductivity

layer	moisture deficit(DF) in % of FC (%)	ECfc soil moist. at FC (mS/cm)	ECe=EC sat. extr. (ECfc/ 2) (mS/cm)	drainage from layer after irr mm
END PERIOD 1				START PERIOD 1
1	15	4.2	2.1	107
2	0	5.9	2.9	79
3	0	6.2	3.1	45
4	0	4.2	2.1	45
END PERIOD 2				START PERIOD 2
1	55	2.6	1.3	131
2	27	3.9	1.9	131
3	0	4.5	2.2	131
4	0	4.2	2.1	131
END PERIOD 3				START PERIOD 3
1	62	2.3	1.1	62
2	41	3.8	1.9	35
3	20	4.1	2	35
4	0	4	2	35
END PERIOD 4				START PERIOD 4
1	70	2.1	1	70
2	46	3.9	1.9	30
3	23	4.6	2.3	10
4	0	4	2	10
END PERIOD 5				START PERIOD 5
1	41	2.5	1.2	42
2	30	4.6	2.3	0
3	37	4.6	2.3	0
4	0	4	2	0
END PERIOD 6				START PERIOD 6
1	36	4.3	2.1	0
2	26	5.7	2.8	0
3	35	5.2	2.6	0
4	0	4	2	0
END PERIOD 7				START PERIOD 7
1	39	6.1	3	0
2	28	6.6	3.3	0
3	35	5.2	2.6	0
4	0	4	2	0

```
Average salinity for the root zone in mS/cm
==========================================================================
period         ECfc           ECe(=2*ECfc)
               soil moisture  soil moisture
               at FC          saturated extr.
               (mS/cm)        (mS/cm)
==========================================================================
 1              4.2            2.1
 2              3.3            1.6
 3              3.4            1.7
 4              3.5            1.7
 5              3.9            1.9
 6              5.1            2.5
 7              6.3            3.1


If available moisture taken at 55% of moisture at field capacity (WP 45%).
==========================================================================

period:  2

Moisture deficit in rooted zone exceeds 55% of field capacity
Irrigation supply insufficient  Correct input data:
Increase irrigation for period   2  with at least  0  mm or
reduce evaporation estimate with that amount if possible and acceptable

period:  3

Moisture deficit in rooted zone exceeds 55% of field capacity
Irrigation supply insufficient .Correct input data:
Increase irrigation for period   3  with at least  7  mm or
reduce evaporation estimate with that amount if possible and acceptable

period:  4

Moisture deficit in rooted zone exceeds 55% of field capacity
Irrigation supply insufficient .Correct input data:
Increase irrigation for period   4  with at least  8  mm or
reduce evaporation estimate with that amount if possible and acceptable
```

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