LINKFLOW, A WATER FLOW COMPUTER MODEL FOR WATER TABLE MANAGEMENT: PART I. MODEL DEVELOPMENT

P. L. Havard, S. O. Prasher, R.B. Bonnell, A. Madani

ABSTRACT. *A computer simulation model, LINKFLOW, was developed to calculate the movement of water during various water table management practices, namely subsurface drainage, controlled drainage, and subirrigation. The model can simulate water movement through a heterogeneous and anisotropic saturated soil and includes an unsaturated flow component with a zone of water extraction by plant roots. The computer program links a newly developed one-dimensional unsaturated water flow model to an existing but modified three-dimensional saturated water flow model, MODFLOW. The water movement is simulated for a region of the field, and results obtained define water conditions in the root zone for a wide range of soil, topography, drain location, and weather conditions. LINKFLOW is unique among soil water flow models because of the following features: 1) it can simulate soil-water conditions beneath a crop on land with varying topography; 2) it can determine 3-D flows from drains in a heterogeneous, anisotropic soil; and 3) it can simulate the effects of different automated control strategies for subirrigation. Results can be presented in tabular format, contour map format, and/or a 3-D surface format to help understanding flow behavior of the system. A subirrigation case simulation is presented to illustrate just one example of the model's use in water table management studies. This article focuses on the development of the simulation model.* **Keywords.** *Water table management, 1-D unsaturated flow, 3-D saturated flow, Topography, Root water extraction.*

Simulation of soil water dynamics under an actively growing crop using mathematical models is usually based on the solution of a governing set of differential equations with appropriate boundary and initial conditions (Remson et al., 1971). Rigorous solutions of combined saturated and unsaturated flows in three dimensions are restricted to small regions due to high computational requirements (Watson, 1974). Pikul et al. (1974) coupled a one-dimensional unsaturated form of Richards' equation to a two-dimensional Bousinesq's equation for saturated flow to reduce the computation requirement.

Models widely used for simulation of water movement between the root zone and tile drainage/subirrigation systems have reduced the computational requirement by simplifying the water flow to vertical in the unsaturated zone and horizontal in the saturated zone. DRAINMOD (Skaggs, 1978) and SWATR (Feddes et al., 1978) are two popular models which use this technique. DRAINMOD uses a water balance approach to solve water movement in the unsaturated profile and combines this with the approximate solutions of Hooghoudt (1940) and Ernst (1975) for saturated flow to or from drains. SWATRE contains a finite difference solution for unsaturated flow and, couples this with approximate relations of Ernst (1975) for saturated flow. Both of these simulation models calculate conditions for only one location in the field, generally the drain pipe mid-spacing location.

The use of approximate solutions for the saturated region, and a single location for unsaturated flow calculations allows these models to simulate water flow conditions for a number of years of weather data in a short computational time. However, as the computational power of microcomputers improve, more computationally intensive models can be used.

The objective of this article is to describe the development of a computer simulation model using computationally efficient methods to simulate the water movement for a selected area of a field with a drainage or subirrigation system in greater detail than current models (Havard, 1995). The model uses a newly developed finite difference solution of Richards' equation to simulate vertical flow in the unsaturated zone and is linked to a modified three-dimensional finite difference solution to simulate flow in the saturated zone. This link has substantially reduced computational requirements compared to a three-dimensional model (Watson, 1974). Yet, LINKFLOW with three-dimensional capabilities is still able to perform detailed water movement studies for areas with heterogenous and anisotropic soils with varying topography using a microcomputer. The model can simulate in two dimensional when homogeneous soil conditions and uniform topography reduce the problem to predominantly two dimensional since flow in the direction of the laterals is insignificant. Moisture conditions in the root zone are simulated and used to determine how effectively a water table management scheme meets crop water requirements.

Article was submitted for publication in April 1994; reviewed and approved for publication by the Soil and Water Div. of ASAE in December 1994.

The authors are **Peter L. Havard,** *ASAE Member Engineer,* Associate Professor, Nova Scotia Agricultural College, Truro, Nova Scotia, Canada; **Shiv O. Prasher,** *ASAE Member Engineer,* Associate Professor, and **Robert B. Bonnell,** *ASAE Member Engineer,* Assistant Professor, Macdonald Campus of McGill University, Quebec, Canada; and **Seyed A. Madani,** *ASAE Member Engineer,* Nova Scotia Agricultural College, Truro, Nova Scotia, Canada.

MODEL DEVELOPMENT

Figure 1 illustrates the major flow processes that occur during the supply of water to the crop. Water flow during water table management takes place in both the saturated and unsaturated zones within the soil. Water flows out of the drains due to a higher water level being maintained by a control chamber connected to the drains than the pressure head present in the soil. This creates a region of high water table near the drain lines resulting in largely saturated flows to the regions between drain lines in the field. Water flow in the unsaturated zone above the water table is mainly vertical. The direction of flow to the plant roots and soil surface, during irrigation periods, is upwards. This water movement will fluctuate diurnally and could be reversed during periods of high precipitation.

Saturation is said to occur when water fills all soil pores. This is the condition which occurs below the water table. Flow in the saturated soil during subirrigation and drainage will be radial flow near the drain and then mainly lateral flow between locations in the field and the drain system. Then, water may flow upward to the unsaturated zone, horizontally to adjacent areas, downward as deep seepage, or in a fashion combining any of these three directions. Calculation of the flows in the saturated zone is done using an existing but modified computer groundwater flow model, MODFLOW.

MODFLOW

MODFLOW is a computer model that can simulate the movement of groundwater in three dimensions (MacDonald and Harbaugh, 1984). It was developed to determine the effect of hydrologic stress or events (such as rainfall, pumped wells, drains, rivers, evaporation) upon a groundwater system. MODFLOW is written in Fortran 77 and is structured so that subroutines are grouped by hydrologic process (modules). The modules are compiled separately and linked together to produce the final, executable file. Only modules and related data sets that are required for a particular simulation need to be used, allowing more efficient use of computing resources. The grouping of the modules also simplifies making additions to the program, since only one module is affected and not the whole program. The program can accept a wide range of boundary conditions, soil, and system parameters (anisotropic, nonuniform, transient saturated water flow parameters).

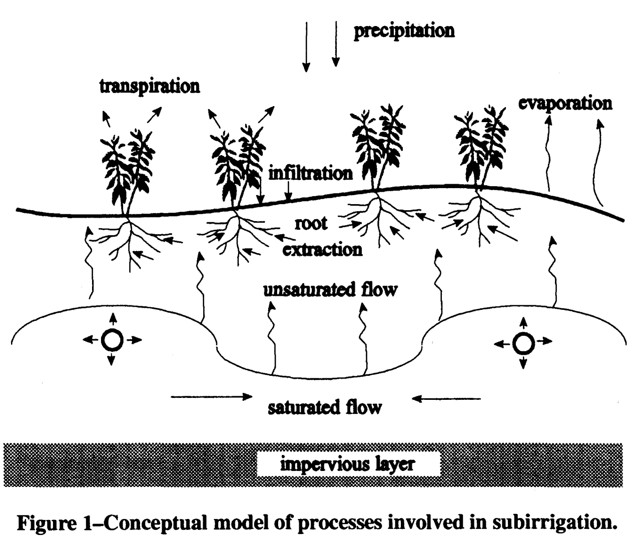


Figure 1–Conceptual model of processes involved in subirrigation.

For this study, MODFLOW was modified to accommodate water table rising through soil layers. The flow budget of MODFLOW needed extensive changes to incorporate the linkage relationships with the unsaturated flow model. Drain flow was determined using the module employed by MODFLOW, which is simply a drain conductance coefficient times the difference in water head between the inside and outside the drain. However, modifications were made to allow for simulation of water flow for several modes of operation like subirrigation, drainage, and controlled drainage, in combination (during a simulation the drains may operate for periods in different modes), and with automated control. Automated control mode is such that the model adjusts the water level in a control chamber according to the water level at some designated point in the field or due to water stress. The change of head in the control chamber in automated control is limited to 5 cm every 24 h and is kept between the ground surface and drain elevation. This step size was selected as a reasonable value and can be changed if desired. This type of simulation provides insight on how a managed system will perform for a given design layout and weather conditions.

UNSATURATED FLOW MODEL

Water movement above the water table is treated as unsaturated flow. The soil profile properties for the unsaturated flow component of the model are treated as homogeneous, and hysteresis is not considered. The model assumes that water infiltrates at the top of the profile during rain events. At the bottom of the unsaturated soil profile, water can drain to or rise from the water table depending on the water potentials present.

The mathematical model of the unsaturated zone assumes vertical flow between the ground surface and the water table. The water table elevation is defined by the saturated flow model.

One-dimensional flow in the unsaturated zone can be described by Richards' (1931) equation with an added root water extraction term (Feddes et al., 1978):

$$C(\psi)\frac{\delta\psi}{\delta t} = \frac{\delta}{\delta z}\left[K(\psi)\left(\frac{\delta\psi}{\delta z}+1\right)\right]-S \qquad (1)$$

where

$C(\psi)$ = soil water capacity (m^{-1}) as a function of pressure head ψ

t = time in days

$K(\psi)$ = unsaturated conductivity function ($m\text{-}day^{-1}$)

z = elevation in the soil profile (m) above a datum

S = sink term ($m^{-3}\text{-}m^{3}\text{-}day^{-1}$ to represent root water extraction)

Equation 1 is used to calculate the temporal and spatial pressure head values which are needed to determine 1) water movement to the saturated zone; 2) infiltration; 3) water extracted by plant roots; and 4) evaporation.

Equation 1 can be solved using numerical techniques. The finite difference solution used here to solve the differential equation uses a predictor (eq. 2) and a corrector (eq. 3), each advancing the solution one-half of a time step (Douglas and Jones, 1963). Figure 2 shows how the nodes in the model are arranged. The predictor written for time step m to m + 1/2 is:

$$\frac{1}{\Delta z}\left[K^{m}_{j+\frac{1}{2}}\left(1+\frac{\psi^{m+\frac{1}{2}}_{j+1}-\psi^{m+\frac{1}{2}}_{j}}{\Delta z}\right)-K^{m}_{j-\frac{1}{2}}\left(1+\frac{\psi^{m+\frac{1}{2}}_{j}-\psi^{m+\frac{1}{2}}_{j-1}}{\Delta z}\right)\right]-S_j=C^{m}_{j}\left(\frac{\psi^{m+\frac{1}{2}}_{j}-\psi^{m}_{j}}{\frac{\Delta t}{2}}\right) \quad (2)$$

where

j = space index

Δz = spacing between nodes (m)

$K_{j+1/2}$ = $(K_j * K_{j+1})^{1/2}$

$K_{j-1/2}$ = $(K_j * K_{j-1})^{1/2}$

(These are the geometric means of the conductivities between nodes [m-day^{-1})]. The corrector is written to advance from time step m + 1/2 to m + 1, as shown by equation 3:

$$\frac{1}{2\Delta z}\left[K^{m+\frac{1}{2}}_{j+\frac{1}{2}}\left(\frac{\psi^{m+1}_{j+1}-\psi^{m+1}_{j}}{\Delta z}+1\right)-K^{m+\frac{1}{2}}_{j-\frac{1}{2}}\left(\frac{\psi^{m+1}_{j}-\psi^{m+1}_{j-1}}{\Delta z}+1\right)+K^{m}_{j+\frac{1}{2}}\left(\frac{\psi^{m}_{j+1}-\psi^{m}_{j}}{\Delta z}+1\right)-K^{m}_{j-\frac{1}{2}}\left(\frac{\psi^{m}_{j}-\psi^{m}_{j-1}}{\Delta z}+1\right)\right]-S_j=C^{m+\frac{1}{2}}_{j}\left(\frac{\psi^{m+1}_{j}-\psi^{m}_{j}}{\Delta t}\right) \quad (3)$$

The advantage of the predictor-corrector technique is its stability in converging to a solution (Douglas and Jones, 1963). If a small enough time step is used, it may not be necessary to iterate. Pikul et al. (1974) used 0.1 to 4 min as suitable time steps in their study.

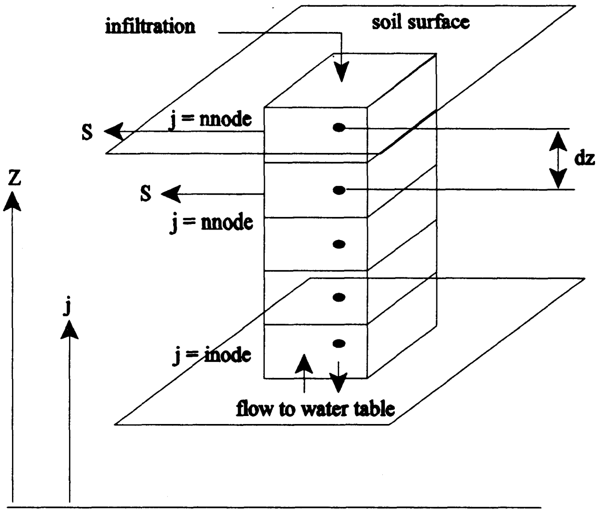


Figure 2–Nodal arrangement for unsaturated flow soil column. 'j' is the node number with a value of 'nnode' at the soil surface, 'rnode' at the bottom of root zone, and 'inode' at the water table.

The finite difference predictor equation (eq. 2) is rearranged into the order shown in equation 4 for solution of pressure heads using the Thomas algorithm (Gerald and Wheatley, 1984). The coefficients A, B, C, and D are solved by rearranging the known components of the finite difference relations with appropriate boundary conditions.

$$-A_j\psi^{m}_{j+1}+B_j\psi^{m}_{j}-C_j\psi^{m}_{j-1}=D_j \quad (4)$$

The zone of active nodal points is bounded by the soil surface at the top and the water table at the bottom, as shown in figure 2. The model varies the number of active nodal points to fit the current water table depth. The flux between the unsaturated model and the saturated model is found by calculating a water budget on the unsaturated flow column (eq. 5) for each time step.

$$q_{wt}=\Delta W-S+I \quad (5)$$

where

q_{wt} = volume of flow per unit area across the water table (m)

ΔW = change in water storage (m)

S = amount of water removed by the plant roots (m)

I = amount of rainfall (m) that infiltrated during the time step

ΔW is determined over a small time step. Since a constant number of nodal points are used during that period, ΔW is determined by the difference in moisture content times the soil volume at each node between the start and end of the time step. A leaf canopy interception value is selected that is representative for the storm character, vegetation species, density of plants, and season. The rate of infiltration is assumed to be less than the conductance of the soil for the surface nodes (the first term within brackets of equation 2 with a saturated surface boundary condition). If the rainfall rate exceeds the maximum allowable infiltration, then excess water is considered ponded on the surface until it can infiltrate. At this stage of the model development, the main emphasis has been placed on the linkage between the saturated and unsaturated flow models. Surface runoff has not yet been incorporated and will be considered in future improvements to the model.

The upper boundary condition is treated as a no-flow boundary (Neumann condition). This means all flows that cross this boundary due to rain (top node) and evapotranspiration (nodes through root zone) are included in the sink/source term of the finite difference relation rather than being a boundary condition.

ROOT WATER EXTRACTION

The root water extraction value, S, in equation 1 is determined in a similar way to that used by Feddes et al. (1978) in SWATR, except for the addition of terms to account for the time of day, root zone depth, and the method of defining evapotranspiration. The root water extraction rate at a given time and location is determined by adjusting the daily potential evapotranspiration for the effects of soil moisture status, time of day, and depth in the soil. The factor dependent on soil moisture status $\gamma(z)$ is defined in equation 6 to account for the ease with which water can be extracted by roots from the soil due to pressure head.

$$
\begin{aligned}
\gamma(z) &= 1 \text{ if } \psi_{50} < \psi < 0 \\
&= 0 \text{ if } \psi < \psi_{pwp} \\
&= \frac{\psi - \psi_{pwp}}{\psi_{50} - \psi_{pwp}}, \text{ if } \psi_{pwp} \le \psi \le \psi_{50} \qquad (6)
\end{aligned}
$$

This equation requires a defined pressure head ψ at each node within the root zone, a permanent wilting point pressure head ψ_{pwp} (m), and a pressure head at 50% available moisture content ψ_{50} (m). The 50% available water content is suggested as a level where irrigation is needed for a number of crops. The program user can select other values to represent more accurately the crop response they wish to simulate.

A linear distribution of root activity with depth (eq. 7) was developed to include the effect of depth on the amount of water that can be extracted at each nodal point in the profile. At RNODE-1 (just below the root zone) (fig. 2) there will be zero root extraction, and the sum of the DEPTHF factors over the nodes in the root zone will be one. The relation for factor DEPTHF is:

$$\text{DEPTHF} = 2\,\frac{(\text{j} - \text{RNODE} + 1)}{(\text{NNODE} - \text{RNODE} + 1)^2} \qquad (7)$$

where

DEPTHF = weighting factor for root distribution with depth below the soil surface
j = node number in root zone
RNODE = node number at bottom of root zone
NNODE = node number at soil surface

Note equation 7 is linear since it is a function of j with RNODE and NNODE being constant during calculations. For the case of the water table being in the root zone, RNODE will be changed to match the water table level.

Equation 8 was developed to account for diurnal variation of evapotranspiration. Factor TIMEF is calculated using the sunrise hour, T_{S1}, the dusk hour, T_{S2}, and time of day TD (times are a fraction of the day, i.e., 8 A.M. is 8/24 day or 1/3). The coefficient TIMEF when multiplied by the daily potential evapotranspiration gives the rate of evapotranspiration at the specified time. This relation was found by integrating a sinusoidal relation equal to the amount of potential evapotranspiration for that day.

$$\text{TIMEF} = \frac{\Pi}{2(T_{S2} - T_{S1})} \sin\left(\Pi * \frac{\text{TD} - T_{S1}}{T_{S2} - T_{S1}}\right) \qquad (8)$$

The root water extraction S(j) for each node within the root zone is the product of these factors multiplied by the peak evapotranspiration rate S_{max} (eq. 9).

$$\text{S(j)} = \text{DEPTHF} * \text{TIMEF} * \gamma(\text{j}) * S_{max} \qquad (9)$$

These procedures allow the simulation to account for depth, time of day, and water potential. Each relation can be updated when other more suitable formulations for different crops are found. The S(j) value for each node is used in the sink term during solution of the finite difference equations (eqs. 2 and 3).

The number of nodes active in the root zone for which equation 9 will be applied depends on the depth of root zone used in the simulation. The user can select a fixed root depth which would be suitable for perennial crops, or a changing root depth with time, that is more suitable for annual crops. The root depth during the growing season can be described by equation 10 developed by Borg and Grimes (1986).

$$\text{RD} = \text{RD}_{max}\left[0.5 + 0.5\sin\left(\frac{\text{DAP}}{\text{DTM}} - 1.47\right)\right] \qquad (10)$$

where

RD = root depth (m)
RD_{max} = mature root depth (m)
DAP = number of days from planting (days)
DTM = number of days to crop maturity (days)

SOIL PROPERTIES

The relationships used to describe the soil water content and hydraulic conductivity versus pressure head are those discussed in Hoover and Grant (1983) or those by van Genuchten (1978). Both approaches are included in the model, so the user may select the one that best describes the available soils data, or the user may use relation coefficients reported in the literature for different soil types.

FIELD WETNESS

A new and innovative method is proposed here to depict the level of stress on the crop as a function of water status in the soil. Equation 11 defines the quantity called WET by using an average pressure head in the root zone and the pressure heads defining a crop's range of performance. WET can be used to spatially indicate the water stress for plants with a single variable.

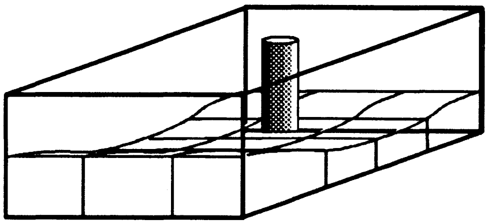
$$
\begin{aligned}
\text{WET} &= 1 - \frac{\psi}{\psi_{air}}, \text{ for } \psi > \psi_{air} \\
\text{WET} &= 0, \text{ for } \psi_{air} \ge \psi \ge \psi_{50} \\
\text{WET} &= \frac{\psi - \psi_{pwp}}{\psi_{50} - \psi_{pwp}} - 1, \text{ for } \psi_{50} > \psi > \psi_{pwp} \qquad (11)
\end{aligned}
$$

WET has a value of plus one in saturated soils which reduces to zero at the air entry value, ψ_{air}. WET equals zero for decreasing pressure heads between the air entry value and 50% available water point (the soil-water range most suitable for root health). For the pressure head range below the 50% level down to the permanent wilting point, ψ_{pwp}, WET changes from 0 to −1. The WET value quantifies the moisture stress over the field. Values greater than zero indicate wet conditions and values below zero indicate dry conditions.

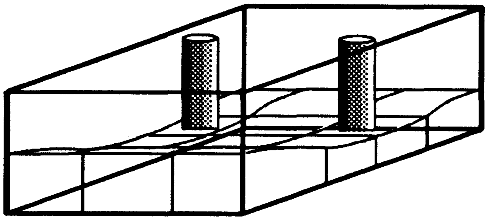
LINKING THE SATURATED AND UNSATURATED MODELS

The unsaturated flow model requires considerable computation due to the nature of its governing equations. The number of unsaturated flow columns linked to the three dimensional saturated model can be varied to balance computational time to the accuracy needed for the analysis. A case study on a very uniform field in terms of topography and soil properties may be simulated with fewer unsaturated flow columns than a more heterogeneous case. The model user needs to gain some appreciation of this by performing several simulations and observing the differences with several levels of linkage. The saturated grid consists of cells that are solved for total head below the water table. Columns representing the unsaturated model are solved for total head above the water table.

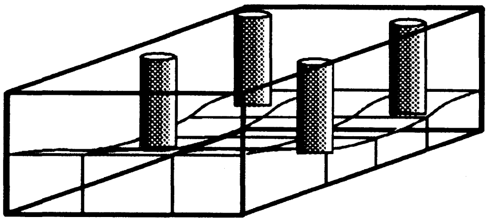
Figure 3 presents different cases of linkage that can be selected between the flow models. Each case has a grid of cells representing the saturated flow model that can have different water table heights. Cylinders that represent the unsaturated flow model are located on top of cells in the saturated model. Four combinations of unsaturated columns and the saturated cells are used in LINKFLOW: 1) the use of one unsaturated column at a single location in the saturated model grid assumes that the same conditions exist for all other locations in the unsaturated zone; 2) the use of an unsaturated column above alternate columns in the saturated model grid, solves values of the unsaturated zone along a single row; 3) the unsaturated column above alternate rows and alternate columns in the saturated model grid is solved and results are interpolated for unsolved locations; and 4) the unsaturated columns are located above each top cell of the saturated model grid. Since the user can simplify the model to different degrees, fast results can be obtained to test the effect of different soil or system parameters. The user may then select for the most comprehensive conditions at the expense of more computational time for a final simulation.



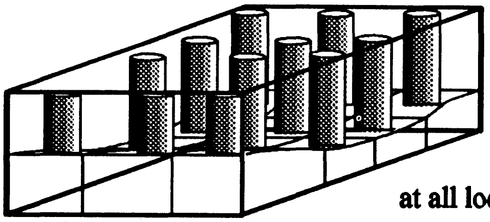
single unsaturated flow column



alternate spaced along one row



alternate spaced along rows and columns



at all locations

Figure 3–The linkage options between the unsaturated model (cylinders) and the saturated model grid.

LINKFLOW

LINKFLOW is the linked unsaturated-saturated groundwater flow computer program that was developed in this study. The program is written in Fortran 77 and has been compiled by the Lahey77 32-bit compiler. The Lahey compiled program runs in a DOS environment and requires a 386 or 486 PC computer to operate.

Performance of LINKFLOW is dependent on the complexity of the flow region and the length of time being simulated. The unsaturated flow model component of LINKFLOW requires the most calculation time due to the dense nodal spacing. Selecting a linkage that does not require all the unsaturated columns to be active will greatly enhance speed of simulation. For example, a simulation for a 60-day period using heterogeneous soil properties and topography for full linkage (every saturated model top cell is linked to an unsaturated model column) required 60 h of computation time on a 33 MHz 486 PC computer. However, using alternate rows and alternate columns requires 15 h. A simple model involving a layered soil and one row of alternate spaced unsaturated columns for 13 days simulation takes 3 min on the same computer. This time reduction is due to the reduction in the number of locations having unsaturated flow calculations being performed.

Interpolating from known locations determines unsaturated flow criteria in areas where calculations were not performed. The inaccuracy will depend on the particular simulation being done. Fortunately, these programs can operate in the background in the Windows or OS/2 environment. This allows continued use of the computer and several simulations to be run at once. Another way to operate is to set up several data sets during the day and run in batch mode overnight.

LINKINP

The LINKINP program makes LINKFLOW user friendly by guiding the user of LINKFLOW in creating new data sets, making modifications to existing data sets, running LINKFLOW, viewing output, creating and viewing contour or surface representations of output data, and making printouts.

EXAMPLE INVESTIGATION

To illustrate the performance of the model, LINKFLOW will be used to simulate subirrigation for a corn crop.

This sample simulation determines the distribution of water supplied to the root zone from the water table during a period of subirrigation over an area of a field. The region is bound by two lateral drain lines and by one main drain, shown in figure 4. Two lateral drains of spacing 15 m and 30 m are simulated in this example, the region has a width equal to the spacing between the two lateral drains, a length of 200 m, with a main drain at one end and none at the other end of the region. Simulations for two different lateral drain spacings will be compared for uniformity of water supplied to the corn crop. The soil properties are the same over the region, with the soil profile having decreasing saturated hydraulic conductivity with depth. A detailed description of the soil properties and layout is given in Havard (1995). The period of simulation will be for three weeks after the beginning of subirrigation. A summary data input requirement for the simulation follows:

Number of columns, rows, layers in grid	9	8	4			
Initial water table elevation (m)	19.25					
Six printout times at (day)	0.5	1	4	10	15	21
Zero rainfall and 5 mm/day PET						
Crop root zone depth (m)	0.5					
Soil surface elevation (m)	20.00					
Thickness of soil layers from surface (m)	0.3	0.4	0.3	1.0		
Saturated hydraulic conductivity (m/day)	1.2	0.9	0.6	0.4		
Anisotropy equals 1						
Drain locations along columns 1, 9 (laterals), and row 8 (main)						
Drain depth (m)	0.85					
Control chamber water elevation (m)	19.75					
Drain conductivity m^2-day^{-1}-m^{-1}	0.4					
Coefficients n, θ_r,θ_{sat}	3.6	0.0780.43				
Moisture characteristic (van Genuchten, 1978)						

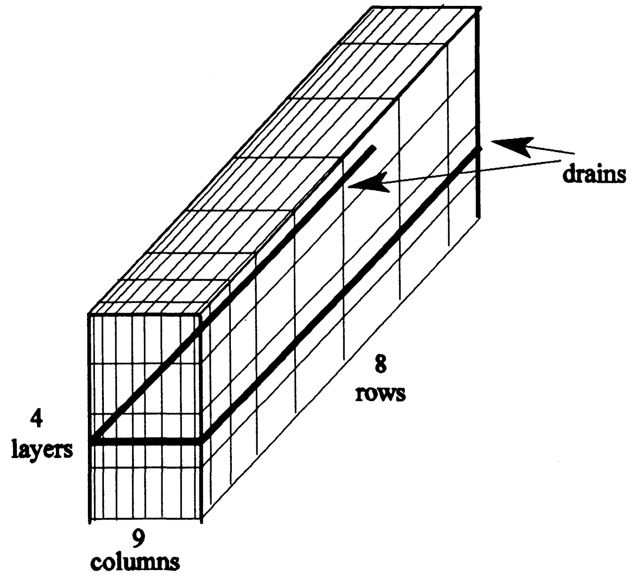


Figure 4–The saturated grid layout sketched to depict layers, columns, and drain location (not to scale).

The grid for the saturated flow model is composed of blocks laid out in an 8 × 9 × 4 matrix (fig. 4). The unsaturated soil moisture characteristic is described using the empirical relations described by van Genuchten, 1978, with the coefficient, n, the residual moisture content, θ_r, and the saturated moisture content, θ_{sat}. It is possible to input soil, topographic, and initial moisture levels for each cell; however, this was not required in this example since properties are assumed to be uniform over the area. The drain lines are located in the center of the third layer, 0.85 m from the soil surface.

RESULTS FROM THE CASE SIMULATION

The elevation of the water table as a function of time is shown in figure 5 at two locations, near the drain and mid-spacing, for the two drain spacings. The simulation with 30-m spacing did not show a rise in the water table at mid-spacing until after 15 days. The mid-spacing water table rose within a week for the simulation with 15-m drain spacing. Near the drain, there was very little difference in the water table levels for the two drain spacings. Figure 6 shows the average moisture content with time of the root zone at the same locations as the water table elevations. Moisture contents for the 30-m drain spacing plot decreased over the 21 days of simulation at mid-spacing. The moisture content reflected the same trend as the water table elevations except the moisture content in the root

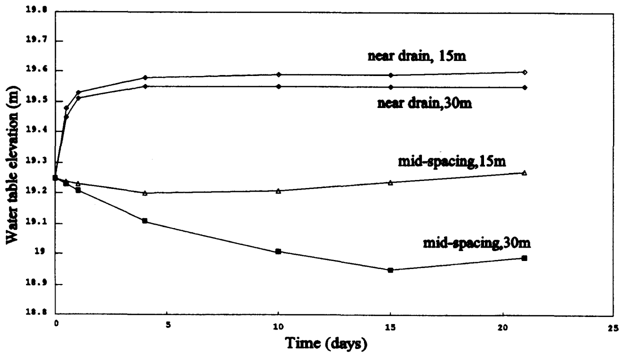


Figure 5–The water table elevations with time for locations near drain and mid-spacing for 15- and 30-m drain spacing.

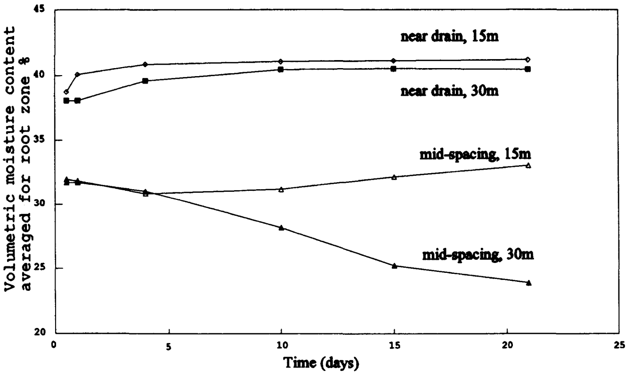


Figure 6–The moisture contents with time for locations near drain and center spacings for 15- and 30-m spacing.

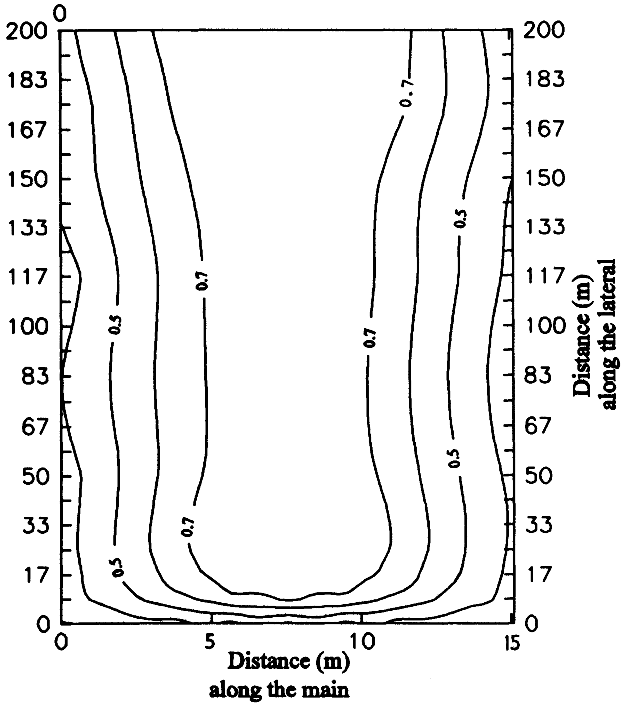


Figure 7–Contour lines (at 0.1-m spacing) for depth to water table (m) after 10 days of subirrigation for 15-m spacing. Note the vertical axis is scaled 10 times the horizontal.

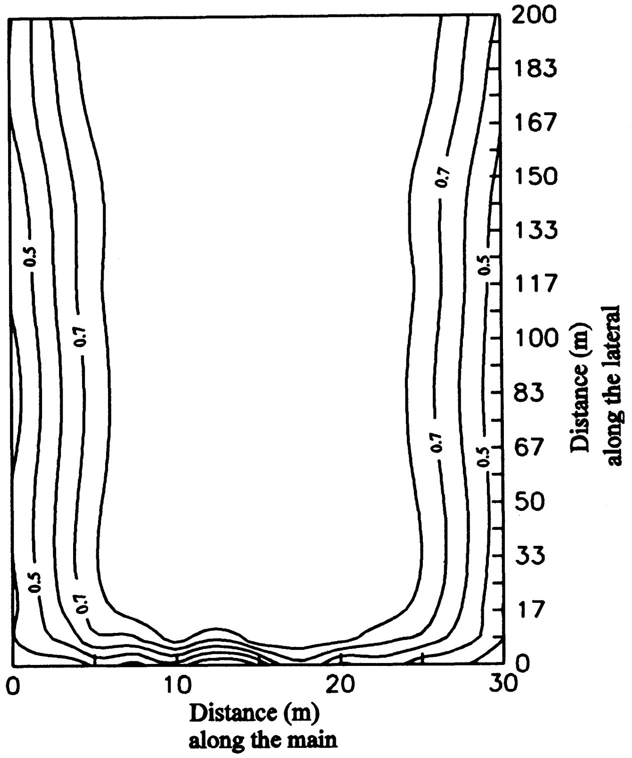


Figure 8–Contour lines (at 0.1 m spacing) for depth to water table (m) after 10 days of subirrigation for 30-m spacing. Note the vertical is scaled five times the horizontal.

zone at mid-spacing for the 30-m case was still decreasing at 21 days. This indicates the importance of not allowing the soil to dry out too much during subirrigation since rewetting can be a slow process.

The plots shown in figure 7 and 8 illustrate the spatial pattern of the water table depths after 10 days for the two drain spacings. The contours are at 0.1-m interval on all plots and the drains are on the left, top, and bottom of each plot. The contour plots clearly show the depth to water table spatially for the region and how spacing would effect the distribution.

The effect of subirrigation on the moisture status in the root zone is illustrated in figures 9 and 10, where the WET values and the area affected is plotted as a function of time. The categories for WET used were severe stress where the WET value is less than –0.5 (very dry), low stress where the WET value is between –0.5 and 0.0 (dry), no stress where WET is 0.0, and aeration stress when WET is greater 0.0 (aeration less than 7%). There was a marked difference in results with the two drain spacings. Neither simulation showed severe stress over the time period. The 15-m spacing in figure 9 showed no low stress conditions but had significant areas of aeration stress. The aeration stress was due to high water tables in the vicinity of the drains. The 30-m spacing in figure 10 had limited aeration stress but showed a significant amount of low stress (47% after 21 days).

These results reflect the situation for one combination of inputs for these two spacings. Changing head levels in the drain would alter the results. The water levels in the 30-m drain spacing case would rise sooner if a higher head was set in the control chamber to the drain lines. The 15-m case suggests one should have lowered the control chamber levels to lower the local water table levels. A proper evaluation of the dynamics of the system would require several simulations for a range of operational and system parameters.

Verification of LINKFLOW with field measurements and further application of the model is given in Havard et al., 1995b c, respectively.

SUMMARY

The formulation of a linked saturated-unsaturated flow model to determine water movement during water table management is described. The model, LINKFLOW, will aid in development of new strategies and feasibility studies for water table management systems. LINKFLOW links a one-dimensional unsaturated flow model to a three-dimensional saturated flow model. The linked models can

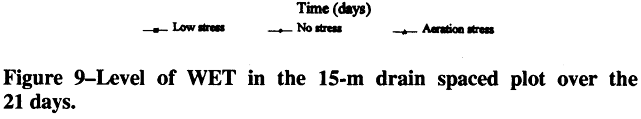


Figure 9–Level of WET in the 15-m drain spaced plot over the 21 days.

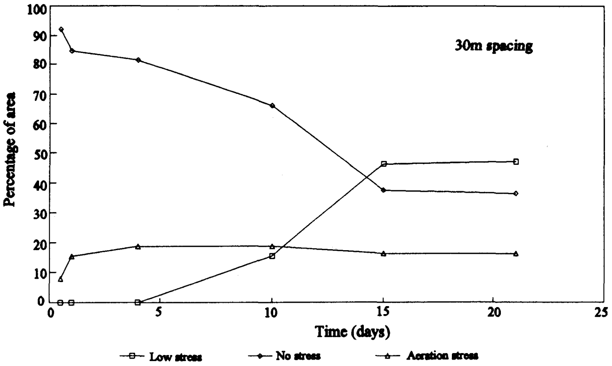


Figure 10–Level of WET in the 30-m drain spaced plot over the 21 days.

account for the effects of topography, soil heterogeneity, and crop water extraction for a region of a field. The case example illustrates the kind of detailed analysis that can be done on water table management systems. This information can be used to determine the effectiveness of a water table management system to provide the optimum moisture conditions to a crop over a growing season.

REFERENCES

Borg, H. and D.W. Grimes. 1986. Depth development of roots with time: An empirical description. *Transactions of the ASAE* 29(1):194-197.

Douglas, J. and B. F. Jones. 1963. On predictor-corrector methods for nonlinear parabolic differential equations. *J. Siam* 11:195-204.

El-Kadi, A. I. 1984. Automated estimation of the parameters of soil hydraulic properties. GWMI 84-12, Int. Ground Water Modelling Centre, Halcomb Research Inst., Butler Univ., Indianapolis, Ind.

Ernst, L. F. 1975. Formulae for groundwater flow in areas with subirrigation by means of open conduits with a raised water level. Misc. Reprint 178, Inst. for Land and Water Management Research, Wageningen, The Netherlands.

Feddes, R. A., P. J. Kowalik and H. Zaradny. 1978. Simulation of field water use and crop yield. *Simulation Monographs.* PUDOC, Wageningen.

Gerald, C. F. and P. O. Wheatley. 1984. *Applied Numerical Analysis,* 3rd Ed. Reading, Mass.: Addison-Wesley Publishing Company.

Havard, P. L. 1995. LINKFLOW, A linked saturated-unsaturated water flow computer model for drainage and subirrigation. M.S. thesis, McGill Univ., Montreal, Quebec, Canada.

Havard, P. L., S. O. Prasher, R. B. Bonnell and A. Madani, 1995b. A water flow computer model for water table management: Part II. Model verification. *Transactions of the ASAE.* (Submitted).

————. 1995c. A water flow computer model for water table management: Part III. Model application. *Transactions of the ASAE.* (Submitted).

Hooghoudt, S. B. 1940. Bijdragen tot de kennis van eenige natuurkundige grootheden van den grond, 7, Algemeene beschouwing van het problem van de detail ontwatering en de infiltratie door middel van parallel loopende drains, greppels, slooten en kanalen, Verslag. *Landbouwk. Onderzoek* 46:515-707.

Hoover, J. R. and W. J. Grant. 1983. Numerical fitting of the Gardener equation to hydraulic conductivity and water retention data. *Transactions of the ASAE* 26(5):1401-1408.

MacDonald, M. G. and A. W. Harbaugh. 1984. A modular three-dimensional finite-difference ground-water model. Program users guide. U.S. Department of the Interior, Reston, Va.

Pikul, M. F., R. L. Street and I. Remson. 1974. A numerical model based on coupled one-dimensional Richards and Bousinesq equations. *Water Resources Research* 10(2):295-302.

Remson, I., G. M. Hornberger and F. J. Molz. 1971. *Numerical Methods in Subsurface Hydrology.* New York: John Wiley.

Richards, L. A. 1931. Capillary conduction of liquids through porous mediums. *Physics* 1:318-333.

Skaggs, R. W. 1978. A water management model for shallow water table soils. Tech. Rep. 134, Water Resoures Research Inst., North Carolina State Univ., Raleigh.

van Genuchten, M. T. 1978. Calculating the unsaturated hydraulic conductivity with a new closed-form analytical model. 78-WR-08, Water Res. Program, Dept. of Civil Eng., Princeton Univ., Princeton, N.J.

Watson, K. K. 1974. Some applications of unsaturated flow theory. *Drainage for Agriculture,* ed. J. van Schilfgaarde. Madison, Wis.: Am. Soc. of Agronomy.