Modelling and Simulation of the Soil Water Regime

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Introduction

Losses of moisture from the soil profile are replaced by the capillary rise of water from the water table. The problem is compounded by the fact that water is evaporated from the soil and plant surfaces, usually at a rate greater than that at which the water can be replaced from beneath by unsaturated flow.

The objective of this study was to develop a simulation model of soil water processes under growing grass using the computer language FORTRAN. The results include: computed evapotranspiration, water table movement, dynamic soil moisture tension and optimum groundwater table.

The model has been used to simulate conditions on research areas of the Sosnowica Experimental Station of the Institute for Land Reclamation and Grassland Farming, Lublin. In this area most of the land consists of meadows and pastures, and much of this grassland is covered with peat soil, which is especially susceptible to drying. In this case water has important consequences in the conservation of the soil.

Development of the model

Water movement in unsaturated soil

The principal aim of this study was to develop a model to predict the water conditions under growing grass. This paper includes a model or programme called GRAGRO which simulates the unsaturated flow of water through the soil, changes in the water table as a result of precipitation and evapotranspiration, and the calculated daily evapotranspiration rate.

For a one-dimensional vertical flow, with z [cm] as the vertical coordinate starting at the soil surface and with positive values in the downward direction, the flux V can be written as:

$$V = -K(\Theta)\frac{dH}{dz} \qquad /1/$$

where:

Θ = the volumetric water content of the soil, $cm^3\ H_2O/cm^3$ soil;
$K(\Theta)$ = the hydraulic conductivity of the soil, cm/s;
H = the total height, cm.

Introducing the concept of continuity and representing the water uptake by roots as a sink term [$cm^3\ H_2O/cm^3$ soil/s] , the time rate of change in the soil water content can be expressed as:

$$\frac{\partial \Theta}{\partial t} = - \frac{\partial v}{\partial z} - s(\Theta) \qquad /2/$$

where t is the time [s].

Combining /1/ with /2/ gives the basic differential equation for soil water flow in the vertical direction:

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial z} \left[k(\Theta) \frac{\partial H}{\partial z} \right] - s(\Theta) \qquad /3/$$

Numerical solutions and simulation language solutions have been developed in the past years with relatively good results. PHILIP /1957/, HANKS and BOWERS /1952/, KLUTE /1952/, and ZARADNY and POWALIK /1971/ have presented types of solutions based on different approaches.

The GRAGRO model simulates the vertical flow in an unsaturated homogeneous soil. The uptake of water by the root system is considered to be a function of the root density, the hydraulic properties of the soil, and time. Water absorbed by the roots is expelled to the atmosphere by the leaves in vapour form. Fig. 1 illustrates the model concepts.

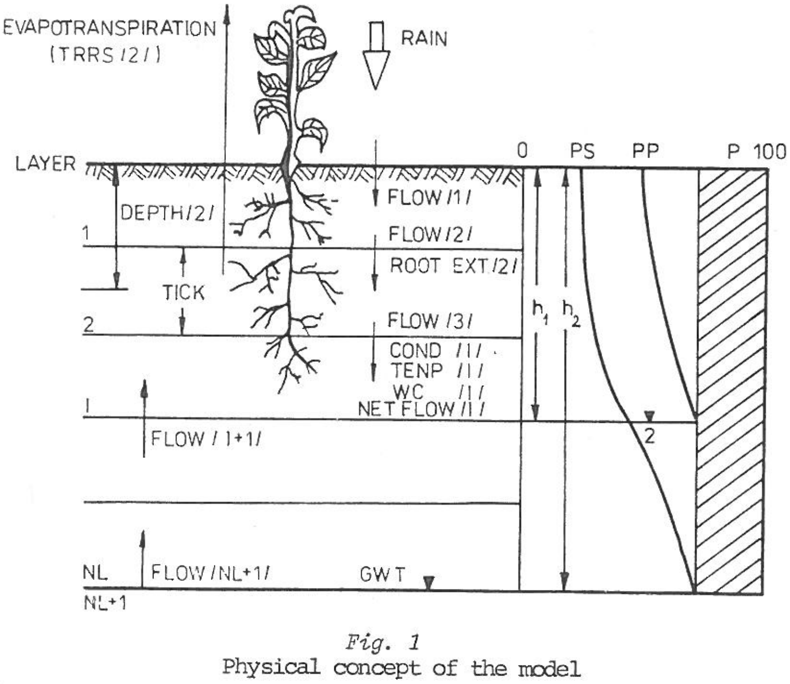

Fig. 1
Physical concept of the model

The soil is divided into small /5 cm/ layers; equations of unsaturated flux and mass conservation are applied to each of them and the water content of each layer is evaluated as a continuous function of time. After setting a group of initial conditions, the simulation runs with a constant time step of ten minutes.

The method for determining the soil moisture in each layer is a simple accounting system, in which the losses and gains of each layer are calculated. Water gain and loss originate from upward or downward flux, from evapotranspiration, or from infiltration after rain.

The GRAGRO model was compared to field data with the water table held at a level of 40 cm in depth. Fig. 2 shows the scheme of functions of the model.

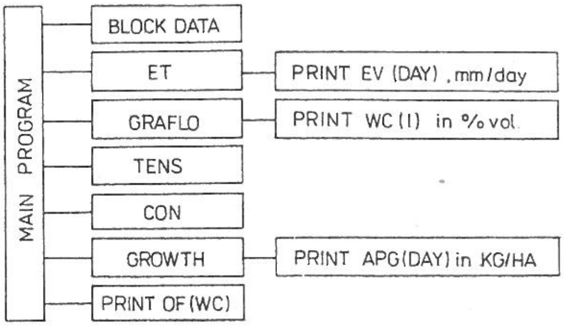

Fig. 2

Scheme of the functions of the model

The moisture-tension relationships or moisture retention curves /pF curves/ for the five soil profiles which give the relationship between tension potential /TENP/ and water content /WC/ have been determined according to the methods described by STAKMAN et al. /1967/ as modified by ZAWADZKI /1973/. Unsaturated hydraulic conductivity as a function of moisture tension was obtained from data published by OLSZTA /1973/ using a technique developed by WIND /1959/. The determination was made on soil samples from five sections of the experimental plots in Sosnowica.

The saturated hydraulic conductivity of the soil was determined by a laboratory method /ZAWADZKI and OLSZTA, 1976/ and in the field by the auger-hole method /BEERS, 1953/ adapted by ZAWADZKI and OLSZTA /1976/. 1973/.

The moisture predicted by the model is used to find the value of the tension in the soil according to the soil-moisture tension relationship /pF curve/, and this value is in turn used to calculate the unsaturated hydraulic conductivity of each layer. Hydraulic conductivity and tension relations are calculated in the subroutines CON and TENS of the model.

Evapotranspiration

Daily evapotranspiration from the crop is calculated from RITCHIE's model /RITCHIE, 1972/ as modified by LAMBERT et al. /1975/ on the basis of the fraction of solar radiation intercepted by the crop surface.

RITCHIE's model predicts the daily evapotranspiration from a crop surface. It applies to a row crop canopy situation in which the water supply to the plant roots is not limited and the crop has not reached an advanced stage of maturation or senescence. After considering the soil surface and plant surface components of radiation interception, the potential evaporation, the rainfall and the net radiation above the canopy, the evapotranspiration is calculated.

Precipitation

Data were obtained from a recording rain gauge located in the field research area. Accumulated rainfall is stored in MAIN in the DATA RAIN statements. Accumulated rainfall is set in MAIN once a day, if RAIN > 0.3 cm.

Computer programme

The programme model GRAGRO was developed in the FORTRAN language. The model was run for 76 days during the growing season, from 5 June to 20 August, 1973, and includes the following subroutines: ET, GRAFIO, TENS, CON, GROWTH /Fig. 2/.

The graphical representation of the daily performance of the management model for section II at Sosnowica is shown in Fig. 3.

The dynamic soil water content is calculated in the MAIN programme; the flow chart for MAIN is presented in Fig. 2.

The object of this investigation was also to find out the depth of groundwater table which would maintain a given field moisture capacity in the root zone layer.

In this case the GRAGRO programme can be used for the simulation of dynamic soil moisture under conditions of constant evapotranspiration and constant water table depth with no rainfall.

Neglecting in this model the Subroutine GRAFIO and the Subroutine ET, and assuming constant evapotranspiration /EV/, the model programme GRAGRO can be used to determine the optimum water table depth as a function of evapotranspiration and capillary rise above the groundwater table.

Results

GRAGRO Programme for the dynamics of water conditions in the soil

The GRAGRO programme is the major contribution of this paper, since it takes into consideration the dynamics of water transport processes, and the simulated results agree well with observed field data.

Simulation of dynamic soil moisture tension, water table depth and evapotranspiration

The management model was tested for the 1973 growing season beginning on 5 June and ending on 20 August, for section II at Sosnowica.

A series of observations made for section II is shown in Fig. 3, which illustrates certain predicted and measured data. Fig. 3 also shows the distribution of rain for the growing season, which was used as an input in the model. The evapotranspiration results as calculated and measured in lysimeters for grass are shown in Fig. 3b. From the comparison of the measured and the calculated actual evapotranspiration it can be seen that the values are close. Only at the beginning of simulation and in the period from June 20-30 are there significant deviations between the calculated and measured evapotranspiration.

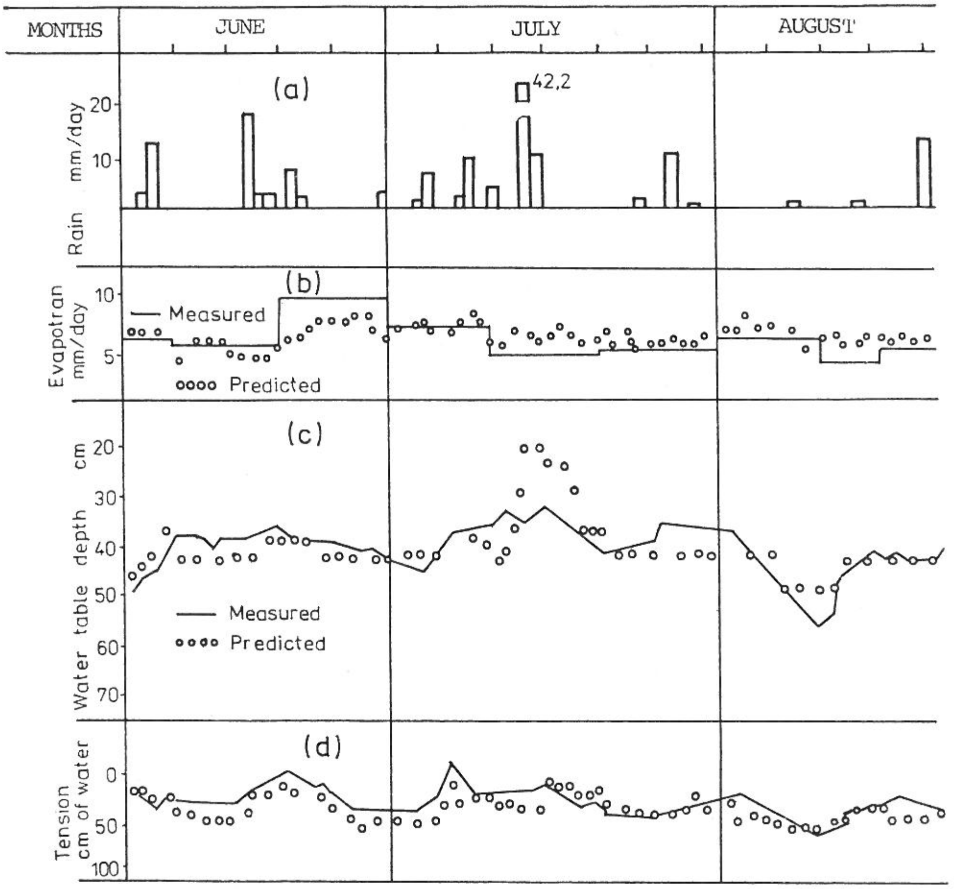

Fig. 3

Measured and predicted water conditions under grass growing on peat soil at Sosnowica, section II

The dynamics of the water table are also very close /Fig. 3c/. Only in the period from 12-17 July, when heavy rain occurred, was the calculated water table much higher than the measured one. During this period, 42 mm of rain fell on 13 July. Part of this rain was probably runoff, but in the model it was assumed that all the rain flowed into the groundwater table. The runoff occurred only during the time when the groundwater table was at the soil surface in the model. The difference between the calculated and the measured groundwater table can be seen during the period when the rain was intense. The value of the calculated soil tension at this time was a little higher than the measured data /Fig. 3d/.

Summarizing the results from the GRAGRO model, it can be said that they are in satisfactory agreement with the results obtained. During the testing of this model, some difficulty was met when simulating the flow of water just under the water table; this difficulty can be removed by reducing the thickness of the layer, or by reducing the size of the integration time step. In general terms, a layer thickness of 2 to 4 cm is appropriate, but in this programme a 5 cm layer thickness was used. The GRAGRO programme may be useful in practice for predicting soil moisture in cases when the groundwater table during the growing season does not fluctuate greatly, and when a rise in the groundwater table occurs as the result of rain, and a fall as the result of evapotranspiration.

Simulation of soil moisture dynamics under conditions of constant evapotranspiration and constant water table depth

The object of this investigation was to find the optimum groundwater table that would maintain a given field moisture capacity in the root zone layer. Summing up, using the GRAGRO programme, the dynamics of soil moisture in the unsaturated zone is calculated as the function of a constant groundwater table and a constant rate of evapotranspiration. Calculations were made for the groundwater tables at depths of 40, 60, 70, 80, 90 and 100 cm, and for evapotranspiration rates of 2, 4, 5, 6, 8 and 10 mm/day, respectively. Fig. 4 presents graphs of the distribution of water content in the profiles as functions of EV for constant groundwater table at depths of 40 and 100 cm. These relations were obtained after twenty days with no rainfall, for section II.

Simulated optimum water table depth as a function of evapotranspiration

The defining conditions for the optimum groundwater table were assumed to be those where the moisture content at a depth of 5-10 cm was approximately equivalent to field capacity.

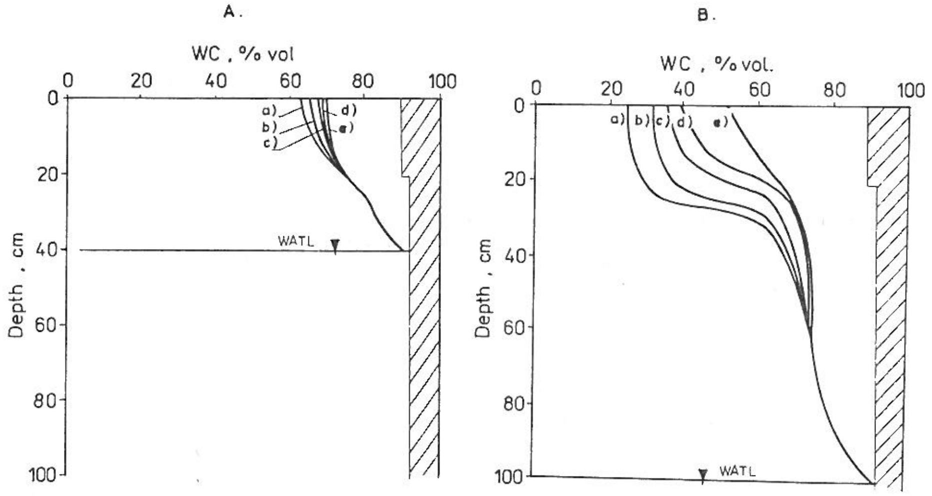

Fig. 4

Simulation of water content distribution after 20 days in a profile of peat soil /section II/ as a function of evapotranspiration, with no rainfall, for a constant groundwater table depth at 40 cm /A/ and 100 cm /B/. a/ EV = = 10 mm/day; b/ EV = 8 mm/day; c/ EV = 6 mm/day ; d/ EV = 4 mm/day; e/ EV = = 2 mm/day

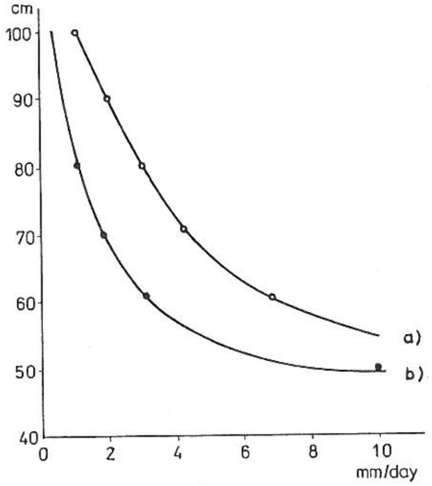

Fig. 5

Simulated relation between optimum water table depth /cm/ and evapotranspiration rate /mm/day/ for water content /WC/ in the 5-10 cm layer of 0.65 cm^3/cm^3 /a/ and 0.60 cm^3/cm^3 /b/. Obtained from a 20-day simulation in section II, with no rainfall

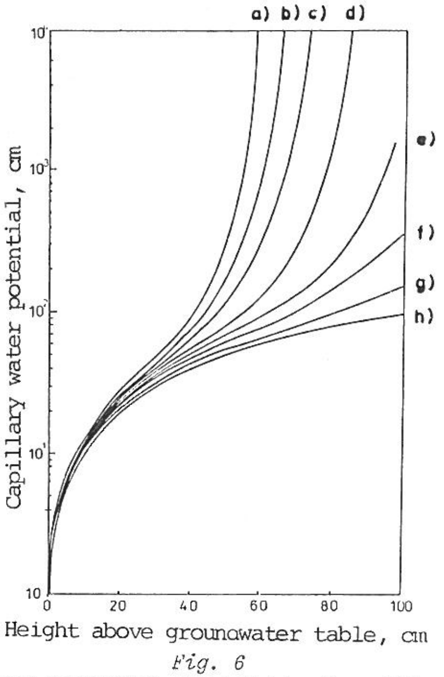

Fig. 6

Relation between water potential and height of capillary rise above the groundwater table at different evapotranspiration rates under steady state conditions on a peat soil at Sosnowica, section II. a/ EV = 10 mm/day; b/ EV = 8 mm/day; c/ EV = 6 mm/day; d/ EV = 4 mm/day; e/ EV = 3 mm/day; f/ EV = = 2 mm/day; g/ EV = 1 mm/day; h/ EV = 0 mm/day

Two cardinal values of moisture content were assumed for the determination of the optimum groundwater table: the field capacity, which corresponds to a tension of pF 2, and the value corresponding to a tension of pF 2.15. The simulated relation between optimum groundwater table and EV is shown in Fig. 5. Having obtained the average value of daily evapotranspiration, for example 4 mm/day, the results show that the optimum water table depth for the investigated soil is 55 cm (curve b/ on Fig. 5).

Simulated height of capillary rise above the groundwater table

The real value of capillary height during the growth of plants is influenced by the physical condition of the soil and the rates of evaporation and transpiration.

Loss of water by evapotranspiration and transpiration during steady state conditions is balanced by the rise of moisture from the groundwater table. The relation between capillary rise above the water table was obtained for a peat soil /Fig. 6/. Fig. 6 indicates the height of capillary rise which will keep a supply of water available for the plants /pF = 2.0-2.5/ equal to 100 cm height for EV = 1-2 mm/day (curve f and g).

For EV = 3 mm/day /curve e/, the height of capillary rise for pF = 2.5 reaches about 80 cm, while for pF = 2, the height is 60 cm above the water table. But for EV = 6 mm/day, at a height of 60 cm, soil suction was 300 cm, and for EV = 8 mm/day 800 cm, which corresponds to what is called "hardly available" water.

The relation in Fig. 6 illustrates the reality of the phenomenon of capillary rise, which may in some cases be useful in practice /e.g. during long periods of drought/.

Summary

In this paper attention has been paid mainly to determining the dynamics of water transport in the unsaturated zone under growing grass.

The uptake of water by the root system is considered to be a function of the root density, the hydraulic properties of the soil, and the time. After setting a group of initial conditions , the simulation runs with a constant time step of ten minutes. The model was compared to field data for section II with the water table held at a depth of 40 cm.

The lack of agreement between the simulated and measured data is sometimes disappointing, but indicates, more than anything else, the areas in which our knowledge is unsufficient.

Hence GRAGRO can be used for predicting soil water transport processes, both when the groundwater table during the growing season does not fluctuate greatly, and when a rise in the groundwater table occurs as the result of rain, or a fall as the result of evapotranspiration.

The GRAGRO programme can be used, after a few changes, to estimate the optimum groundwater table and the height of capillary rise, as influenced by the hydraulic conductivity of the soil.

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