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SIMULATION OF THE SOIL WATER REGIME FOR GRASSLAND IRRIGATION

W. Olszta, P. Gliński

Department of Water Management, Lublin Technical University, Nadbystrzycka 40, 20-618 Lublin, Poland

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A b s t r a c t. The principle aim of this study was to develop a model to predict the water processes under growing grass. This paper includes: the GRAGRO model simulates the vertical flow in an unsaturated homogeneous soil, changes in the water table as a result of precipitation and the calculated daily evapotranspiration. The object of this study was to complete the GRAGRO model with a subroutine IRRDEC, which simulates the prediction of the irrigation, and calculates the amount of water which must be supplied to carry out this irrigation. This model was tested and model results were compared with measured values observed in several lysimeters with different ground water tables on a peat soil located in Sosnowica, Poland.

K e y w o r d s: water flow in soil, evapotranspiration, crop production, irrigation predicted

INTRODUCTION

Under the prevailing climate in Poland, nearly every summer dry spells occur that cause the water demand of the atmosphere to exceed the ability of the root system to extract water from the soil. Consequently there is a growing interest for supplemental irrigation, especially on intensively managed dairy farms located on drought sensitive soils.

The model GRAGRO considers water movement in and through the soil in response to pressure head gradients in accordance to the equations of Darcy and continuity. Water extraction by roots is accounted for by a sink term. The approach requires specification of the soil water retention and of hydraulic conductivity curves, upper boundary conditions of precipitation and potential evapotranspiration and an appropriate lower boundary condition. The growth rate of the crop is defined as a hyperbolic function of the growth factor water (i.e., transpiration) with the maximum growth rate as the upper limit and the efficiency of water utilization as the initial slope of the hyperbola.

The results of the investigations presented in this paper point out a possibility of calculating the value of the function $\Theta(z,t)$ and the growth of the dry mass of meadow plants by the method of mathematical modelling of leaf temperature and transpiration on the basis of the climatic conditions and the physical and water properties of soil. There is still a lack of an empirical verification of the calculations obtained, therefore the results illustrate the theoretical aspects of the water movement in the unsaturated zone of soil profile.

APPLIED MODELS AND EQUATIONS

Water flow in the soil with plant water uptake

Physical concept of the GRAGRO model is presented in Fig. 1. The water balance module was used to characterize the soil water regime. One dimensional vertical unsaturated flow in

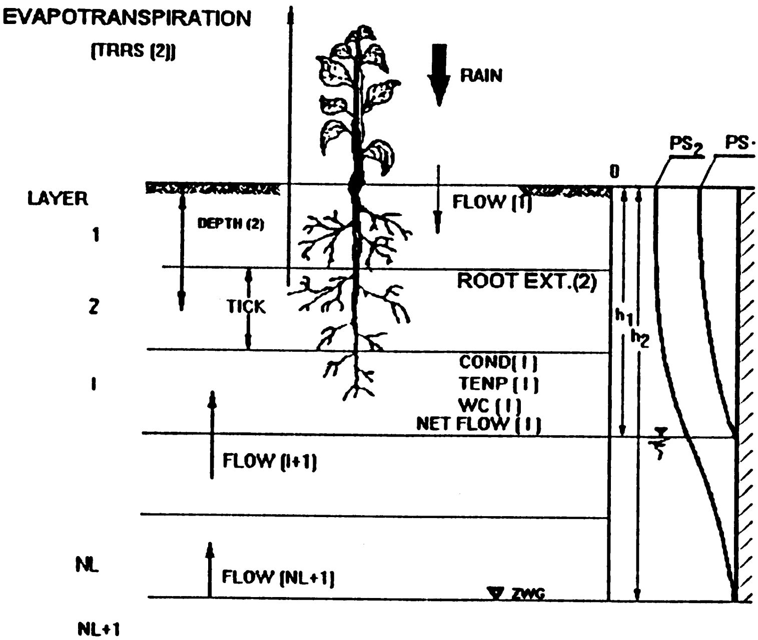

Fig. 1. Physical concept of the model.

a heterogeneous soil-root system was described by the following general form of the soil-water flow equation:

$$\frac{\partial h}{\partial E}=\frac{1}{C(h)}\,\frac{\partial}{\partial z}\left[K\,(h)\left(\frac{\partial h}{\partial z}+1\right)\right]-\frac{S(h)}{C(h)} \quad (1)$$

where h is the soil-water pressure head (cm); $C=\partial\,\Theta/\partial h$ differential water capacity (cm^{-1}); z is the vertical coordinate (cm); K is the hydraulic conductivity ($cm\ d^{-1}$) and S is a sink term representing the water extraction rate by plant roots ($cm^3\ cm^{-3}\ d^{-1}$). The latter was defined by:

$$S(h)=a(h)\,S_{\max} \quad (2)$$

where $a(h)$ is a dimensionless function of pressure head and S_{max} is the maximum possible water extraction by plant roots. Feddes *et al.* [3] assumed in the interest of practicality a homogeneous distribution of $S_{\max}$ with depth according to:

$$S_{\max}=\frac{T_p}{|Z_y|} \quad (3)$$

where Tp is the potential transpiration rate ($cm\ d^{-1}$) and Z_y is the effective rooting depth (cm).

For liquid water uptake by roots (S) the equation can be written as [1,3]:

$$S=\frac{(\Psi_s-\Psi_l)}{(r_{soil}+r_{rp})} \quad (4)$$

where r_{soil} is the soil hydraulic resistance for flow of water in the soil and from the soil to the root hair surface, r_{rp} is the plant resistance for liquid water transport from the roots to the mesophyli of the leaves, Ψ_l is the leaf water potential taken as a mean value of the layer of leaves where the rate of transpiration is the most rapid, and Ψ_s is the soil water potential in the root zone. The values of the unsaturated hydraulic conductivity $K\,(\Psi_s)$ were estimated from the soil water potential Ψ_s.

The relationships of hydraulic conductivity and presume head on water content are presented in Fig. 2.

The upper boundary conditions at the soil surface include daily rainfall and potential evapotranspiration (ET_{pot}) data.

$$E_{pot} = \frac{\delta Rn + C_p \rho_a (e_o - e_d)/r_a}{(\delta + \gamma)\, l} \qquad (6)$$

where E_{pot} - potential evapotranspiration flux (kg m^{-2} s^{-1}), δ - coefficient numerically corresponding to the derivative of the saturated vapour pressure as with air temperature T_a

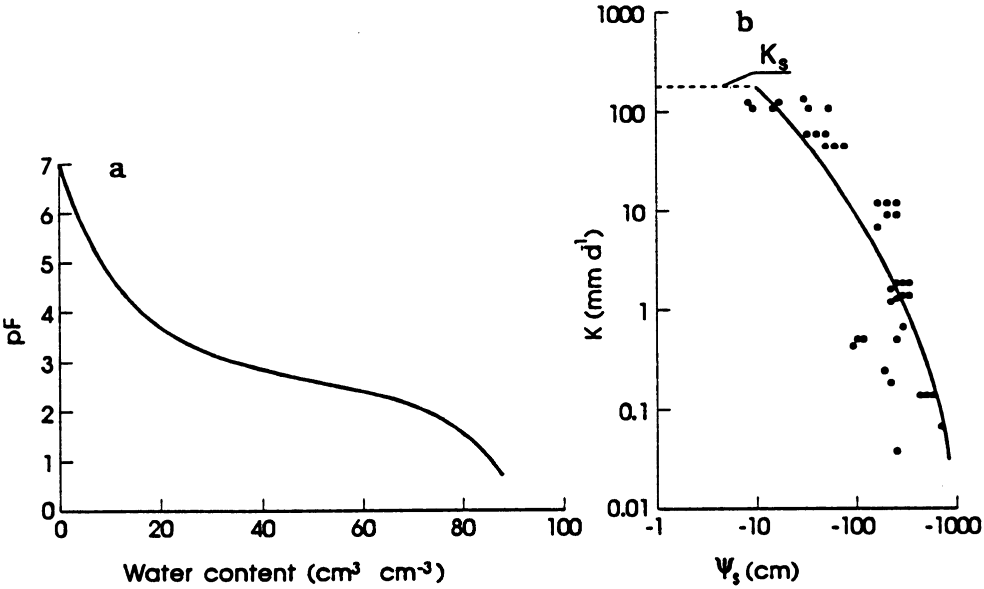

Fig. 2. The moisture retention curve (a) and hydraulic conductivity (b) of the soil profile used for the simulation.

Evapotranspiration

Potential transpiration ET_{pot} can be calculated from the relation:

$$ET_{pot} = E_{pot} - ES_{pot} \qquad (5)$$

where E_{pot} is potential evapotranspiration from both the crop and the soil. ES_{pot} is potential evaporation from only the soil surface. The E_{pot} values are most often derived from Penman's equation. This uses a combination of energy balance and transport of water vapour. Basically, Penman applied this combination method to a water and a soil surface. The final formula for E_{pot} is (for details see Zaradny [8] and Olszta [6]):

(hPa ^{o}K^{-1}), Rn - net radiation (Wm^{-2}), C_p - specific heat of the air at constant pressure (J kg^{-1} ^{o}K^{-1}), ρ_a - density of the air (kg m^{-3}), e_o - water vapour pressure of saturated air at air temperature T_a (hPa), e_d - actual vapour pressure (hPa), γ - psychrometer constant (hPa ^{o}K^{-1}), l - latent heat of evaporation (J kg^{-1}), and r_a - aerodynamic resistance (s m^{-1}).

The value r_a can be determined under conditions of natural stability if the plant height and the wind velocity are known (for instance from the formulae and tables given by Feddes *et al.* [3]).

The crop production model (GROWTH)

For the estimation of potential and actual production rates, Feddes *et al.* [3] gave a mathematical derivation of growth rate as a function of normalized water use with the upper limit and the efficiency of utilization of water as the initial slope of the function. Daily actual dry matter growth rate q_a (kg ha^{-1} day^{-1}) was calculated as:

$$\left[1-\frac{q_a}{AW/\Delta e}\right]\left[1-\frac{q_a}{q_m}\right]=\zeta \qquad (7)$$

where A is the maximum water use efficiency (kg ha^{-1} cm^{-1} mbar); W is the 'productive' water used. Δe is the average vapour pressure deficit of the air (mbar); q_m is the maximum possible growth rate (kg ha^{-1} day^{-1}); and ζ is a mathematical parameter (ζ=0.01).

The daily dry matter growth rate q_a was divided among three biomass fraction: harvestable grass and roots. The ratio harvestable sward:roots was held constant at 65:35 throughout the growing season. The high proportion of harvestable sward in this ratio was justified by an optimum nitrogen fertilization level (180 kg N ha^{-1}). In this model (Subroutine GROWTH) a daily dry matter growth calculated from equation:

$$q_a = 29.45 + 0.95\,LV - 0.001\,LV^2 \qquad (8)$$

where q_a - net photosynthesis (kg ha^{-1} day^{-1}), LV - visible radiation (cal cm^{-1} day^{-1}).

Also established, the effect of temperature is used (Subroutine GROWTH) to calculate the actual dry matter production of grass (APG). Other data used in Subroutine GROWTH were daily radiation on clear days, the light intensity on overcast days is 0.2 times. To calculate the visible radiation on overcast days multiply visible radiation by coefficient which is dependent on the degree of light intensity on overcast days.

Irrigation on scheduling (IRRDEC)

The model GRAGRO was completed with a Subroutine IRRDEC, which simulates the prediction of the capillary rise irrigation, and calculates the amount of water which must be allowing the water table to rise. Soil moisture, described as a function $\Theta(z,t)$ can change in time (t) and in different depth (z), within a wide range of moisture, i.e., from critical moisture Θ_k, through an optimum moisture Θ_0 to maximum water saturation of soil.

The predicting or undertaking of the decision to carry out the irrigation consist of maintaining, in the root zone of the soil profile, the value of the function $\Theta(z,t)$ in the range:

$$\Theta_k < \Theta(z,t) < \Theta_0$$

At the point Θ_k the limited growth occurs. Thus this value will be the main criterion for undertaking a decision of irrigation. The model allows actual controlling the ground water state and the moisture distribution in soil profile. A block diagram of the Subroutine IRRDEC, whereas the tabulation of the subroutine and complete technical documentation is given in another paper [5].

SIMULATION RESULTS OF THE GRAGRO AND IRRDEC MODEL

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

A series of observations made for section II (H=60 cm) is shown in Fig. 3, which illustrates certain predicted and measured data. Figure 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 lisymeters for grass are shown in Fig. 3. From the comparison of the measured and the calculated actual evapotranspiration it can be seen that the values are close.

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.

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. The results for 40 cm depth rooting

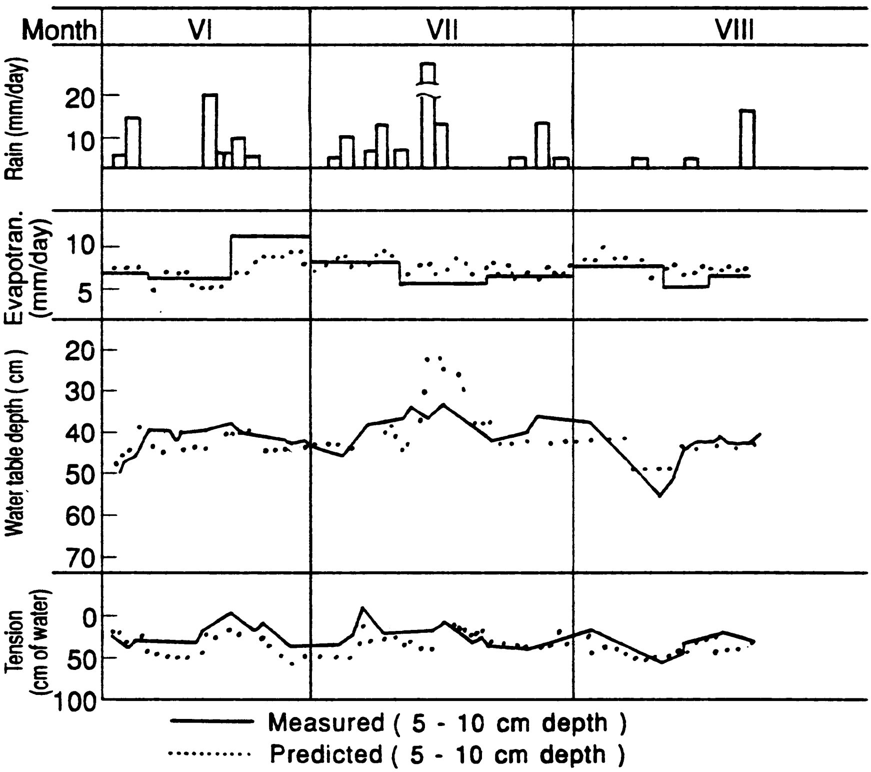

Fig. 3. Measured and predicted water conditions under grass growing on peat soil at Sosnowica, section II (H=60 cm).

distribution illustrate the drop of the water table h_{zw} during growing season (April-June), but the availability of water to plants was still good (Fig. 4).

The ratio of ET_{act}/ET_{pot} reached the minimum value, i.e., 0.35 for spacing 30 m in August [7].

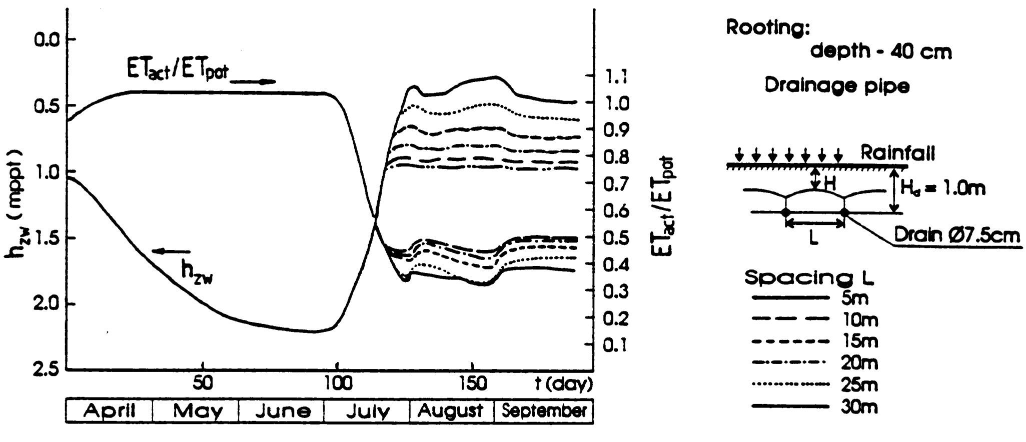

Fig. 4. Position of the ground water table h_{zw} and values of ratio evapotranspiration ET_{akt}/ET_{pot}.

Simulation for irrigation scheduling and crop production

The calculation of irrigation results are presented in Fig. 5 and the following parame-

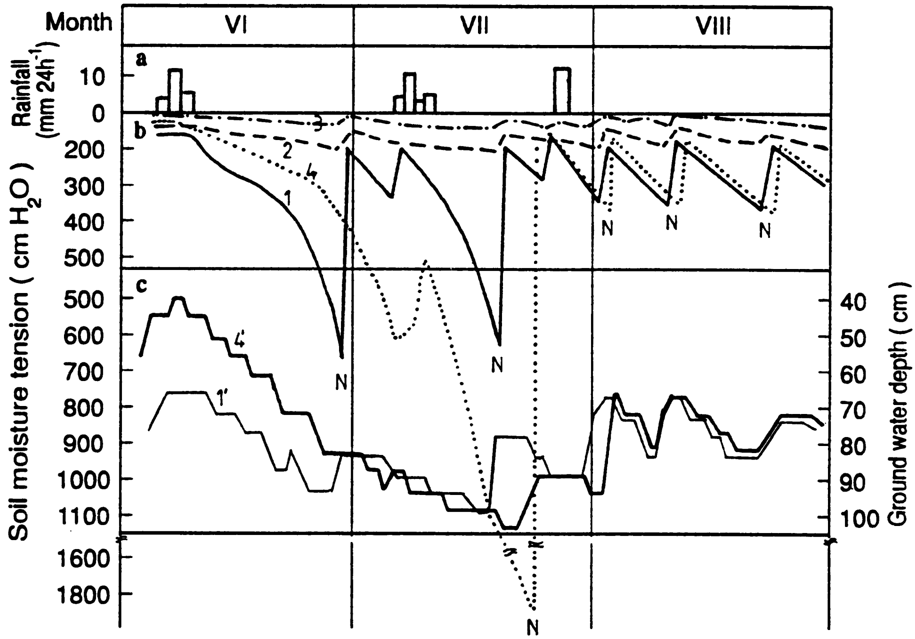

Fig. 5. Rainfall (a), dynamics of soil moisture tension (b) and ground water depth (c) during a long-lasting period of drought, irrigation (N) applied in section II at Sosnowica (from calculations).

ters are given: a - rainfall distribution, b - dynamics of soil moisture tension at layers 5-10, 20-30, and 55-60 cm depth (lines 1, 2, respectively) for the initial state of the ground water table, i.e., H=80 cm, and moisture tension at a depth of 5-10 and 55-60 cm for the state of the ground water table at H= 60 cm (line 4, 3), c - dynamics of the ground water states (lines 1' - for H=80 cm and 4' for H=60 cm).

Significant differences between the suction of the upper layer (5-10 cm) and the deeper ones were observed. It can be seen that the ground water state at H=80 cm, five irrigations were carried out, whereas for the H=60 cm, only four were carried out during simulation. It should also be stressed that for the H=80 cm the first irrigation was done on June 28, and that for the H=60 cm on July 23 (line 4).

The results of the calculations on the grass growth were obtained in Fig. 6, where line 1 presents the 24 h increases of the dry mass of grass with the H=80 cm, the dashed line presents the mean value of the 24 h increase for the second and the third swath obtained from the experimental field of the Institute of Melioration and Grassland Farming at Sosnowica, from the climatic condition noticed in 1983.

Prognosis of water relations for the long-lasting period of drought (in this case as theoretical experiment optimally determined) allows for an economic solution and explains many important practical problems connected with irrigation.

SUMMARY AND CONCLUSIONS

In this paper, attention has mainly been pointed to determining the dynamics of water and heat transport in the unsaturated zone under growing grass (GRAGRO model). The uptake of water by the root system is considered to be a function of the root density, hydraulic

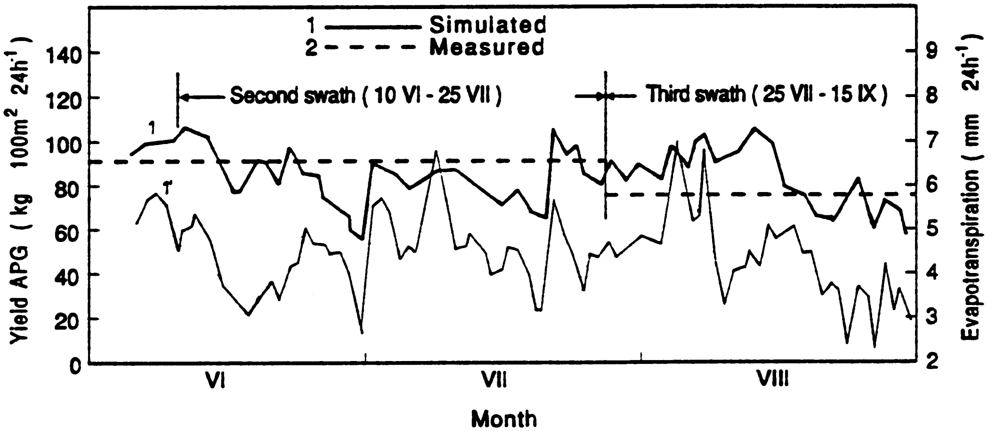

Fig. 6. Simulation of the value (APG) dry mass of grass (1) and evapotranspiration (1') for a section I (H=80 cm) at Sosnowica under irrigation applied.

properties of the soil, and time. The model was compared to field data for section II with the water table held at 40 cm depth. The lack of agreement between the simulated and measured data is sometimes disappointing, but indicates more than anything else in the areas in which our knowledge is lacking. Based on those results, we may conclude that this method can be used to understand better the response of grass to water deficits as water for irrigation is limited and a chance to predict optimal irrigation.

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