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SIMULATION OF AN IRRIGATION SYSTEM FOR PEAT SOILS*

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A b s t r a c t. This article presents the use of selected numerical models which provide prognoses of water changes in soil profile, in steady state and dynamic conditions. The examples presented concern the estimation of the capillary rise range (model PODSIAK), the dynamics of moisture change in the profile of irrigated soil (model SWATREZ) and the economics of irrigation (model UGWTPN – IRRDEC), in peat soils conditions. Using the mathematical model methods described, the authors indicate significant facilities in comparison with traditional methods of land reclamation improvement and the process of regulation design.

K e y w o r d s: soil physics, water movement simulation, irrigation, peat soils

INTRODUCTION

Land reclamation is a rather expensive undertaking; proper design is very important. Potential investors of reclamation systems want to obtain a good design in as short a period of time as possible with a favorable prognosis for its functioning in the future. Traditional design methods do not give such possibilities. Probably the only solution is the mathematical model method, which allows the simulation of reclamation system work, in various soil and plant conditions.

Processes connected with water flow on soil-atmosphere and soil-plant boundaries are among the most difficult to solve. Their external limitations cannot be precisely determined in most cases, except as "potentials". For this purpose, many computer simulation programs exist which try to approximate reality.

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This paper presents basic equations for the description of water flow in soil, taking into account water uptake by plants and real boundary conditions. The equations were used to compute moisture dynamics in a layered soil profile containing variable drain-pipe spacing (program, SWATREZ) [3,9], the capillary rise range of water in soil profile, in steady stage conditions (program PODSIAK). A simulation of the prediction of the time and the amount of water for irrigation (the subroutine IRRDEC of UGWTPN program) is also presented.

All calculations presented below were done based on the conditions at the Stawek-Stoki peat valley [4,5] located near the City of Lublin and on the experimental station of the Institute for Land Reclamation and Grassland Farming in Sosnowica [6,7], located also on peat.

APPLIED MODELS

To solve the assumed design problem as outlined in the introduction, the authors used the following computer programs: EVAPOT [9] for estimating potential evapo-transpiration, PODSIAK [9] to estimate soil capillary rise properties and SWATREZ for the simulation of the dynamics of moisture change in the soil profile. The model UGWTPN (subroutine IRRDEC) was used for the estimation of the dry mass yield of plant and irrigation scheduling. [6,7].

Water flow in soil with plant – water uptake

The physical concept of the SWATREZ model is presented in Fig. 1.

Dynamic water flow in soils with growing plants was simulated by the SWATREZ [3] program based on Richard's equation, supplemented by the source factor $S(h)$, which reflects the water uptake by plant roots:

$$\frac{\partial h}{\partial t} = \frac{1}{C(h)} \frac{\partial}{\partial z}\left[k(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - \frac{S(h)}{C(h)} \tag{1}$$

where: h – soil water potential (cm), t – time [d], $C(h)$ – differential water capacity, $K(h)$ – water conductivity (cm d^{-1}), z – vertical coordinate [cm], $S(h)$ – source factor (transpiration etc.) (cm d^{-1}).

The flow from or to the drain (ditch) is calculated by formula [1]:

$$q_1 = \frac{\phi_1 - \phi_2}{T} \tag{2}$$

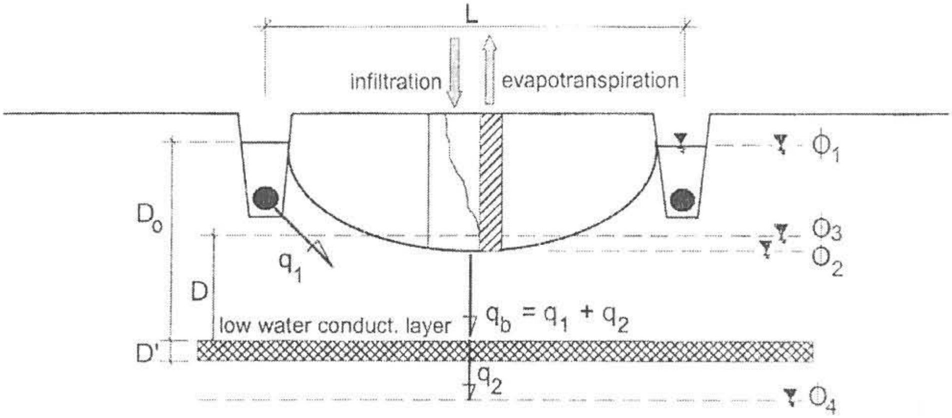

Fig. 1. Physical concept of the SWATREZ model

where: ϕ_1 – water level in drain (ditch) (cm), ϕ_2 – groundwater level in the middle of drainage spacing (cm), T – drainage resistance (d), calculated from the Ernst [2] formula;

$$T = L\omega + \frac{L^2}{8\sum K_i D_i} \tag{3}$$

where: L – drainage spacing (m), K_i – saturated water conductivity of i-layer, for horizontal flow (cm d^{-1}), D_i – thickness of i-layer (m), w – radial resistance (d m^{-1}), calculated by:

$$\omega = \frac{1}{\pi K_r} \ln \frac{CD_o}{u_z} \tag{4}$$

where: D_o – thickness of saturated soil layer, below the water table in drain [m], C – constant, for homogenous layer C=1.0, K_r – saturated water conductivity for radial flow (cm d^{-1}), u_z – drain wetted profile (m).

The flow from or to the lower layer is calculated as:

$$q_2 = \frac{\phi_3 - \phi_4}{C_o} \tag{5}$$

where: ϕ_3 – average water level in the subject territory (cm), ϕ_4 – piezometric groundwater level in layer with low water conductivity (cm), C_0 – vertical resistance of that layer (d).

The solution of the Eq.(1) needs the definition of the series of boundary conditions, such as rainfall, infiltration, potential evaporation and transpiration, height of water level in the drain or ditch and the groundwater level. It is also necessary to estimate the parameters of objective soil environment.

To determine the upper boundary conditions, the authors used meteorological data, comprising temperature, relative humidity, wind velocity, rainfall and actual insulation, collected for the Stawek-Stoki valley. The potential evaporation and transpiration values were calculated using program EVAPOT [4] based on the Monteith, Rijtema and Ritche formulas:

$$EV \cdot L_{up} = A \cdot \frac{\delta R_{net} + \dfrac{c_p \rho_a (e_a - e_d)}{r_a}}{\delta + \gamma} \tag{6}$$

$$ES = \frac{0.0352 \cdot \delta}{\delta + \gamma} R_{net} \cdot e^{-0.39\,LAI} \tag{7}$$

where: EV – evapotranspiration stream (g m^{-2} s^{-1}), ES – evaporation stream (g m^{-2} s^{-1}), L_{up} – latent heat of vaporization (hPa), A – constant value, connected with various units calculations, σ – the first differential of function called the curve of saturated vapor pressure, by air temperature, ρ_a – air density (kg m^{-3}), R_{net} – radiation net, calculated using actual insulation (W m^{-2}), c_p – water specific heat (J kg^{-1} K^{-1}), e_a – actual pressure of water vapor (hPa), e_d – pressure of saturated water vapor (hPa), r_a – diffusion resistance of water vapor (s m^{-2}), γ – psychrometer constant, LAI – index of leaf surface.

The lower boundary condition, the groundwater level, was determined based on the assumed water level in drainage, using resistance theory [3] included in program SWATREZ

Additionally the authors used the PODSIAK [9] program based on the Darcy law, which make possible the simulation of capillary rise range "z" (cm) of water in soil profile, in conditions of steady state output:

$$z = -\int_0^h \frac{dh}{\dfrac{q_j}{K(h)} + 1} \tag{8}$$

where: q_j – elementary flow intensity (cm d^{-1}).

This model doesn't concern the dynamics of moisture change, but facilitates the estimation of soil properties, degradation degree and also the results of the calculations obtained which can be used as the first approximation of lower boundary conditions for the SWATREZ model.

Irrigation scheduling

Soil moisture, described as the function $\theta(z,t)$ can change in time (t) and at different depths (z), within a wide range of moisture, i.e., from critical moisture θ_k, through optimum moisture θ_o to maximum water saturation of soil θ_{sat}. If the value θ is presented on the axis as below:

then the prediction or undertaking of a decision to carry out irrigation consists of maintaining, in the root zone of the soil profile, the value of function $\theta(z,t)$, in the range:

$$\theta_k < \theta(z,t) \leq \theta_o$$

At point θ_k, limited plant growth occurs. Thus this value will be the main criterion for undertaking the decision to water. The value θ_o is proposed as optimum moisture, which corresponds to pF = 2.0.

In improvement practices, the determination of the irrigation dose (d_n) is reduced in calculating the deficits between evaporation and rainwater supply and capillary rise, as well as soil water retention for a certain period of time. Then, knowing the ground water state and the moisture distribution in the soils profile, the amount of water necessary to carry out irrigation can be calculated, according to the simple scheme presented in Fig. 2.

In conformity with the denotations in Fig. 2B the net dose (d_n) upon the area unit is:

$$d_n = \sum_{i=1}^{n}(\theta_{1_i} - \theta_{2_i}) + \sum_{i=n+1}^{m}(\theta_{sat} - \theta_{2_i}) \qquad (9)$$

where: i – successive 5 cm thick layers, n – a number of 5 cm layers in the soil profile counted from the surface to a depth of h_1, m – a number of layers in the soil profile counted from a depth of h_1 to h_2 (h_2 – the depth of water table in soil

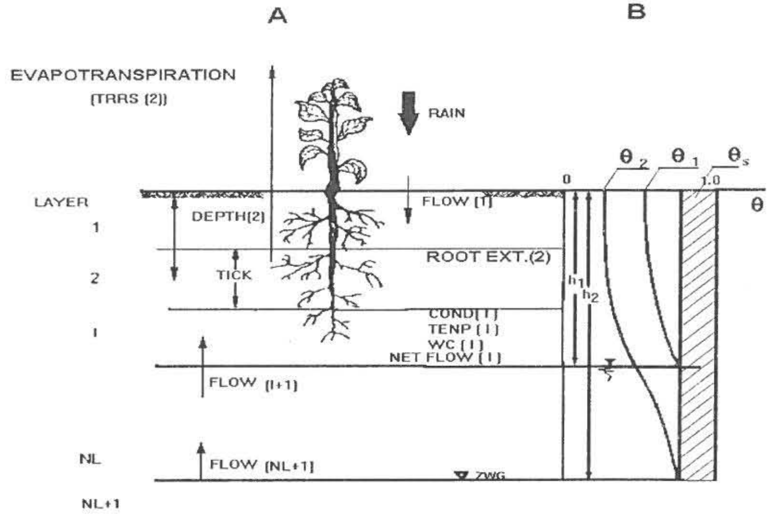

Fig. 2. Physical concept of the soil profile moistening model UGWTPN

for $\theta = \theta_2$), θ_1 – optimum water content (cm^3 cm^{-3}), θ_2 – water content at beginning of irrigation (cm^3 cm^{-3}), θ_{sat} – water content under saturation (cm^3 cm^{-3}).

The value of h_1 is calculated on the basis of the function numerically determined [6]. The θ_1 value is counted from the pF curves, whereas h_2 and θ_2, that is, the actual level of the ground water and the moistening of the soil profile being searched are given by model UGWTPN.

The whole process of computer simulation for the Stawek-Stoki peat valley (the PODSIAK and SWATREZ programs), had been based, except for the soil parameters just presented, i.e., the upper and lower boundaries, on the following assumptions: the object will be equipped with a drainage system with a constant water level, irrigation water will be taken only from local sources (Stawek River) and connected with it, irrigation can be done only once a week. Additionally, soil suction pressure, in the middle of the root strata (12.5 cm) should not fall below pF=2.7 for any period longer than 7 days. Simulations were done with climatic conditions noticed in 1994.

The simulations for the Sosnowica experimental object (sub-routine IRRDEC of UGWTPN program) takes into account the influence of soil moisture variations $\theta(z,t)$ on plant growth. Another condition which decides for or against irrigation is the economic evaluation of the effectiveness of irrigation consisting of calculating the ratio of yield loss, caused by the drop in soil moisture, to the costs of the prospective irrigation.

RESULTS AND DISCUSSION

The simulated investigation of the capillary rise of soil profiles demonstrates the significant differences on the objective valley territory. The example of the investigation results are shown in Fig. 3. Profile 8 represents the peat zone at the Stawek River and the No. 10 – peat zone located about 300 m from that river.

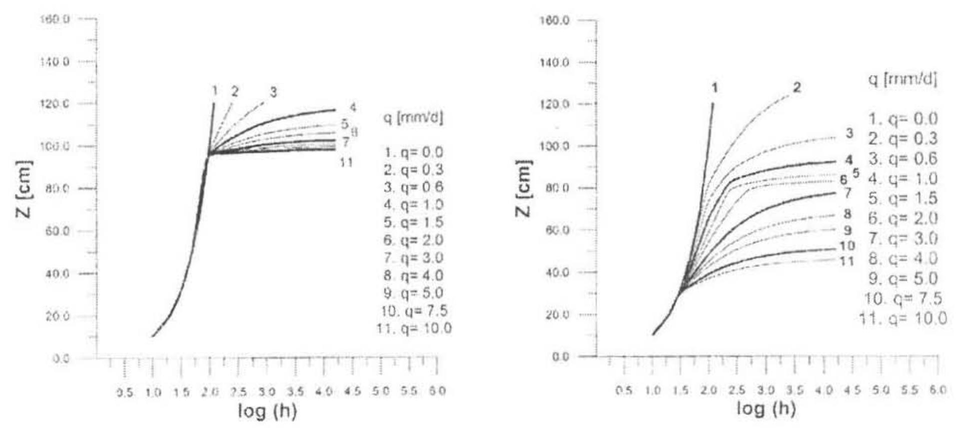

Fig. 3. Capillary rise properties for two different profiles of Stawek-Stoki valley, left: profile No. 8, right: profile No. 10

The simulations performed show that holding the groundwater level at a depth of 60 cm, satisfies water demand for average, seasonal, "in vegetation" evapo-transpiration. This level doesn't allow periodically higher evapo-transpiration values to be satisfied, which gives rise to significant moisture lack in soil profiles. It is of the utmost importance to simulate the dynamics of moisture change in soil profiles and take into consideration additional irrigation.

This simulation, for the 1994 vegetation season, was done using the SWATREZ model. The investigation considered optimum drainage spacing, also the amount and height of additional periodical irrigation which stopped degrada-tion processes and help plant growing. It assumed also that additional irrigation cannot be more frequently than once a week.

Figure 4 shows an example of simulation results for profile No. 10, including evapo-transpiration and rainfall.

Figure 5 presents the comparison of simulation results contained in soil water potential changes at a depth of 12.5 cm, for additional irrigation, made for drainage spacing 8 m.

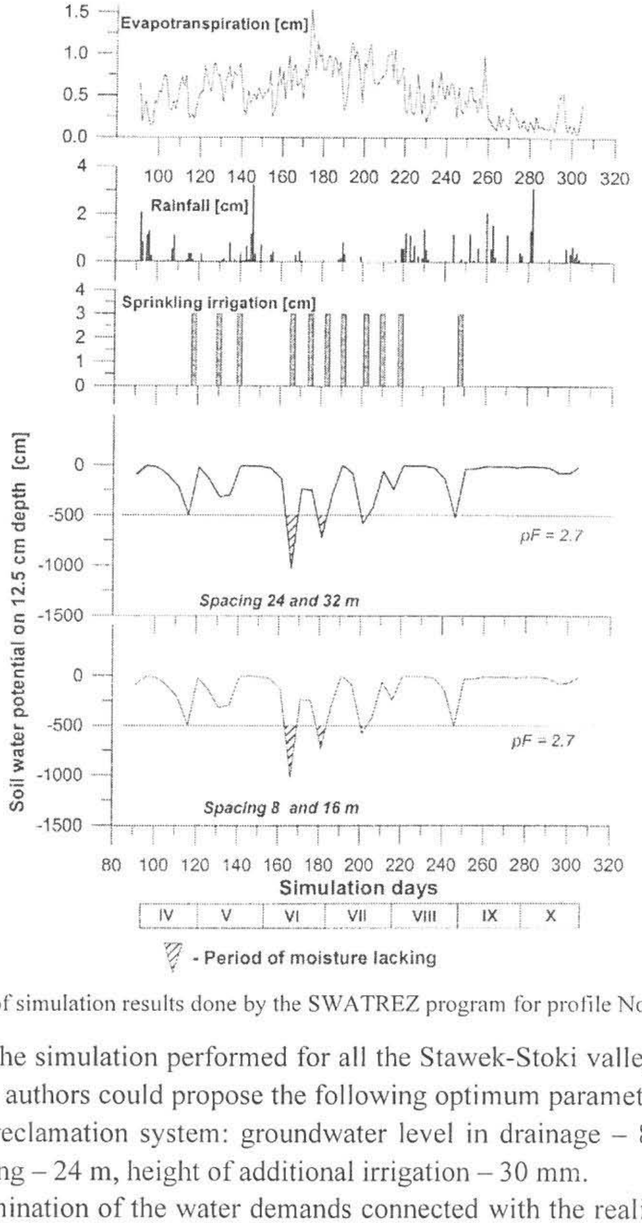

Fig. 4. Example of simulation results done by the SWATREZ program for profile No. 10

Based on the simulation performed for all the Stawek-Stoki valley profiles investigated, the authors could propose the following optimum parameters to the designers for a reclamation system: groundwater level in drainage – 80 cm depth, drainage spacing – 24 m, height of additional irrigation – 30 mm.

The determination of the water demands connected with the realization of the proposed water relations was done in three stages. At first, the irrigation height was determined, connected with lifting the groundwater level to the optimum 80 cm. Next the water demand for a territory chosen earlier was calculated, as result of both irrigation levels.

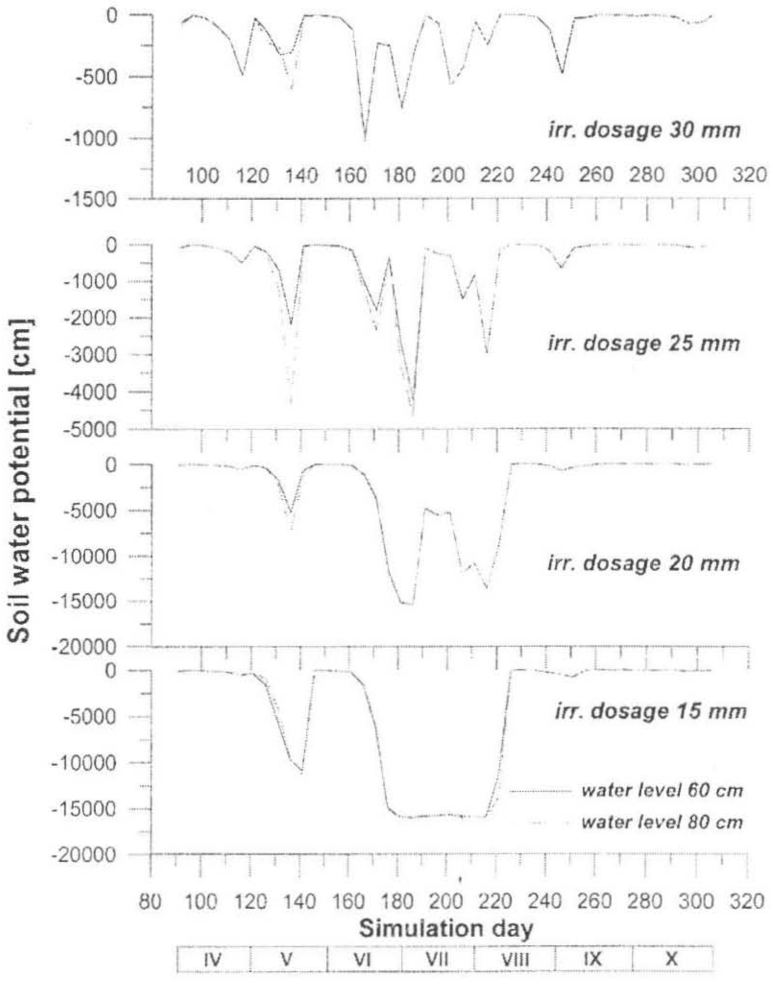

Fig. 5. The comparison of simulation results contained the soil water potential changes at a depth of 12.5 cm, for various additional irrigation levels, made for drainage spacing 8 m. The assumed water level in drainage 60 and 80 cm depth. Example of profile No. 10

Solution for long-lasting drought periods and irrigation prediction

The calculation results obtained using the IRRDEC model for the Sosnowica object are presented in Fig. 6A for the drought period. The following parameters are given: a – rainfall distribution, b – dynamics of soil moisture tension at layers 5-10, 25-30, and 55-60 cm depth – lines 1, 2, 3 (respectively) for the initial state of the ground water table, i.e., H = 80 cm, and moisture tension at a depth of 5-10 cm for the state of the ground water table at H = 60 cm (line 4), c – dynamics of the groundwater states.

Significant differences between the suction of the upper layer (5-10 cm) and the deeper ones were observed. It proves that capillary rise cannot prevent the violent drying of the root zone and therefore, suction at a depth of 5-10 cm reached 600 cm of the water column for the initial H = 60 cm (line 4) on July 5, that is after 27 days of rainless weather, whereas that for the depth of H = 80 cm was, in the same day, 1500 cm of the water column. The differences are equal to about 1000 cm. and lasted till the end of the simulation period, i.e., until August 5. The difference of the initial (instantaneous) states of ground water (part c in Fig. 6B) at the beginning of the simulation process reached 20 cm, while at the end of simulation is decreased to zero.

The results of calculations during the 24 h growth of the dry mass of hay and quantities of water used for transpiration, obtained from simulation, are presented in Fig. 6d. At the initial state of H = 80 (curve 1), the mean value of the 24 h increase of the dry mass of hay (APG) reached about 100 (kg ha^{-1} d^{-1}) at the end of the calculation period August 3rd.

Similarly as for the former solution, the calculation was carried out with application of capillary rise irrigation (Fig. 6B). It can be seen that for the ground water state at H = 80 cm five irrigation were carried out, whereas for the H = 60 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 the H=60 cm on July 23 (i.e., 25 days later).

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

The prognosis of water relations for long-lasting periods of drought (in this case as an inward experiment optimally determined) allows the economic solution of many important practical problems connected with irrigation.

CONCLUSIONS

The paper presents an example of computer simulation methods for the estimation of improvements and regulations in water relations compared to traditional

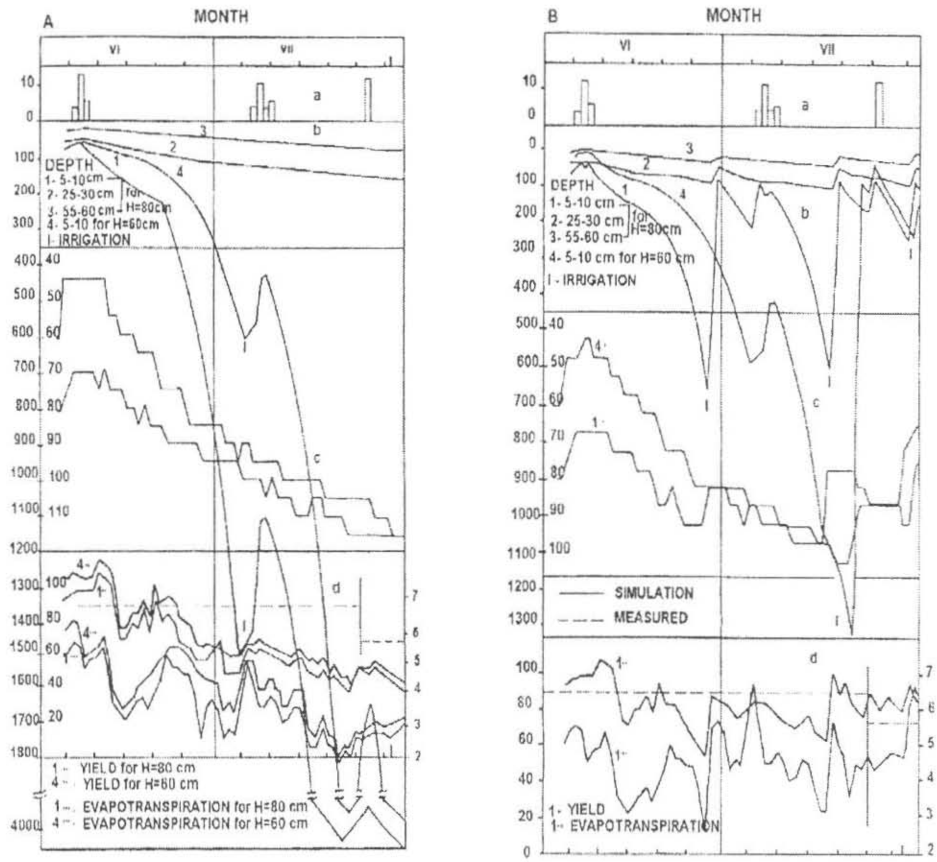

Fig. 6. Rainfall (a), dynamic of soil moisture tension (b), ground water depth (c) and dry mass of yield and transpiration (d): A (left) – for a long-lasting period of drought, B (right) – for a long-lasting period of drought under irrigation (N)

methods. The determination of the optimum parameters of a reclamation system are done by simulating the effect of their exploitation in assumed meteorological and plant conditions. Before the simulation process it was necessary to estimate the parameters of the soil's environment. From that point of view, the necessity of joint collaboration between practice designers and scientists is clearly visible.

Of course it is very necessary to continue the investigation in order to create and verify new, more satisfied models. The authors of the paper are now working on field experimental objects for verification of the present models. The next paper will present the results of that work.

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SYMULACJA SYSTEMÓW NAWADNIAJĄCYCH W WARUNKACH GLEB TORFOWYCH

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S t r e s z c z e n i e. W artykule zaprezentowano zastosowanie wybranych modeli numerycznych umożliwiających prognozowanie stosunków wodnych w profilu glebowym, zarówno w ustalonych, jak i nieustalonych warunkach. Przedstawione przykłady obejmowały wyznaczenie zasięgu wzniosu kapilarnego (model PODSIAK), dynamiki zmian uwilgotnienia nawadnianego profilu glebowego (model SWATREZ) oraz ekonomiki nawodnień (model UGWTPN - IRRDEC), w warunkach gleb torfowych. Autorzy, wykorzystując opisane metody modelowe, wskazują na znaczne ułatwienie prac projektowych związanych z melioracją obszarów torfowych w stosunku do metod tradycyjnych.

S ł o w a k l u c z o w e: fizyka gleby, symulacja ruchu wody, gleby torfowe