Int. Agrophysics, 2000, 14, 73-81

SCHEDULING OF IRRIGATION AND DRAINAGE USING NUMERICAL METHODS

W. Olszta[1], *H. Zaradny*[2]

[1]Department of Water Supply and Waste Water Disposal, Lublin Technical University, Nadbystrzycka 40
20-618 Lublin, Poland
[2]Hydroengineering Institute, Polish Academy of Sciences, Kościerska 7, 80-953 Gdańsk, Poland

Abstract. In this paper the HZAR and UGWTPN - models are described. The HZAR programme is used for the description of water flow in the soil with plant water uptake and for the account of drain - pipe spacing. The UGWTPN (subroutine IRRDEC) for the estimation of dry mass yield of plant and irrigation scheduling is given.

Keywords: water balance in the soil - crop - atmosphere system, drain pipe spacing, irrigation predicting, plant growth

INTRODUCTION

Processes related to water flow on the soil-atmosphere and soil-plant boundaries are among the most difficult to solve. It is so due to since external limitations (i.e., boundary conditions) cannot be precisely determined, in most cases, except in a potential form which means the maximum possible flow. The actual response of the system to a given set of conditions depends on its ability to transport water upwards (in the case of evaporation) or downwards (in the case of infiltration). Also, in the case of water flow from the soil into plant, filtrability of the soil plays an important role in the actual flow, together with availability of soil water for plants.

This paper presents basic equations for the description of water flow in the soil, taking into account uptake by plant and boundary conditions. The equations were used to compute moisture dynamics in a layered soil profile containing a variable drain-pipe spacing (programme HZAR), [6,7].

The subroutine IRRDEC for the simulated prediction of time and amount of water to carry out irrigation is also presented in this paper.

APPLIED MODELS

The HZAR programme is used for the description of water flow in the soil with plant water uptake. The PHZLICZ programme for planning drain-pipe spacing and the model UGWTPN (subroutine IRRDEC) for the estimation of dry mass yield of plant and irrigation scheduling was used [3,4].

The water flow in the soil with plant water uptake

For the soils with growing plants, water flow is described by the Richard's equation, supplemented by the sink term S which reflects water uptake by plant roots [7]:

$$\frac{\partial}{\partial x_i}\left[k^r(h)\left(k^s_{ij}\frac{\partial h}{\partial x_j}+k^s_{i3}\right)\right]+S=$$

$$\left[C(h)+S_S\beta\right]\frac{\partial h}{\partial t} \qquad (1)$$

where : $k^r(h)$ - relative hydraulic conductivity ($0 \le k^r \le 1$), k^s_{ij} - conductivity tensor at saturation, h - soil water pressure head, $C(h) = \partial\theta/\partial h$ - soil water capacity, θ - volumetric water content in the soil, S_S - specific storage of the system soil-water, β - coefficient ($\beta = \theta/\theta_s$, where θ_s - water content at saturation), t - time, x_i ($i = 1, 2, 3$) are spatial coordinates ($x_3 = z$ - vertical).

The general Eq. (1) is parabolic. For a particular case, $\theta = \theta_s$, and $S_S = 0$, the equation becomes elliptic. Eq.(1) is nonlinear because soil parameters $k(h) = k^r(h) \cdot k^s$, C and S depend on the function $h(x_i, t)$.

The sink term S represents the volume of water taken up by the roots per unit bulk volume of soil per unit of time; ($cm^3 cm^{-3} s^{-1} = s^{-1}$). Models from literature, e.g., Zaradny and Maciejewski [8], which is a modification of the model proposed by Feddes *et al.*[2] was used to calculate this term.

According to Feddes, the sink term S in Eq. (1) depends on boundary conditions (potential transpiration ET^{pot}), rooting depth of the plant (L_k) and distribution of soil water pressure head (h) in the root zone. This is the simplest version of the model. A modified version is also available. Here root distribution density as a function of depth, $RDF(z)$, and the effect of daily transpiration rate on the availability of soil water are also considered. The function is shown in Fig. 1.

To find a particular solution, the values h_1, h_2, h_3, and h_4 depicited in Fig. 1 must be estimated.

The studies carried out during grass growing season at polder Bielnik in Żuławy (the Delta area of the River Vistula, north part of Poland, latitude 54°10'N and average altitude of about 0.0 m) had a good fit of calculated results to data at $h_3' = -400$ cm (for $ET^{pot} \geq 5.0$ mm/day) and at $h_3'' = -1000$ cm (for $ET^{pot} \geq 1.0$ mm/day) and for the linear relationship of h for intermediate values of ET^{pot} [6].

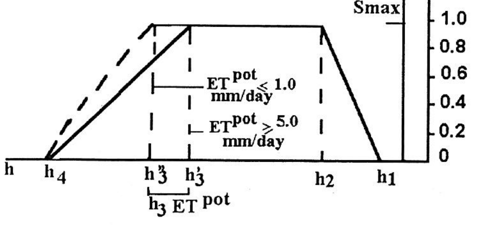


Fig.1. The sink term $S(h)$ according to Feddes *et al.* [2] with further modification by Zaradny [7].

For proposed sink term $S(h)$ the relation (2) has been satisfied:

$$ET^{pot} \geq ET^{act} \int_0^{L_k} S(h)dz = S_{\max} \int_0^{L_k} \alpha(h)dz \tag{2}$$

where: $S_{max} = ET^{pot}/L_k$, L_k - the depth of the root zone, $\alpha(h)$ - factor related to the actual value of $h(z)$ in the root zone.

The drain space calculation

The PHZLICZ programme is based on the Hooghoudt's formula [3] which can calculate drains space L in the drains:

$$L = \sqrt{\frac{8KDh}{q}} \tag{3}$$

where: KD - transmission of water conducting layers, h - high water table above the drain in the half of drain space L, q - water outflow from the drain., or $q = q_p$ where q_p - the determinant precipitation of area under consideration.

The KD value was calculated from the formula:

$$KD = \bar{k} + k^* d_e \tag{4}$$

where: $\bar{k}$ - the medium value of the saturated hydraulic conductivity in the soil layer above drain, k^*- as above but in the soil layer below drain, d_e - equivalent thickness of water conducting layer below drain.

For general the Hooghoudt's formula which is known as the Laby's formula, the value d_e is estimated from:

$$d_e = \frac{L}{8F_H} \tag{5}$$

$$F_H = F_r + F_h = \frac{1}{\pi} \ln \frac{\sqrt{2D}}{d_o} + \frac{\left(L - D\sqrt{2}\right)^2}{8DL} \tag{6}$$

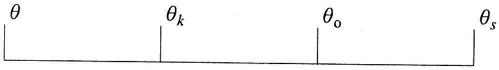
where: F_H - coefficient accounting for the influence of geometrical properties of the flow zone, F_r - as above but it is a component accounting for radial flow, F_h - component accounting for horizontal flow, D - actual soil thickness of the water conducting layer below the drain, L - drain space, d_o - diameter of the tile drain.

The Eq. (3) for $q = q_p = 10$ mm day^{-1} (estimated for the case under consideration) has the following form:

$$L = 28.28\sqrt{KDh}\ . \qquad (7)$$

Irrigation schedule

Soil moisture, described as a 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 an optimum moisture θ_o to the maximum water saturation of soil θ_s. If the θ value is presented on the axis:



then prediction or decisions to be taken for the irrigation consists in maintaining, values of the function $\theta(z, t)$, in the range given below in the root zone of the soil profile:

$$\theta_k < \theta(z,t) \le \theta_o . \qquad (8)$$

At the θ_k point limited plant growth occurs. Thus this value will be the main criterion for undertaking a decision of watering. The θ_o value is proposed as an optimum moisture, which corresponds to pF 2.

In the melioration practice determination of irrigation doses (d_n) is reduced to calculations of deficiency levels, between evaporation and water supply from rainfall and the capillary rise, as well as soil water retention for a certain period of time. Then knowing the ground water state and moisture distribution in the soil profile, the amount of water necessary to carry out irrigation can be calculated according to a simple scheme presented in Fig. 2.

Accoding to denotations in Fig. 2B the net dose (d_n) upon the area unit is:

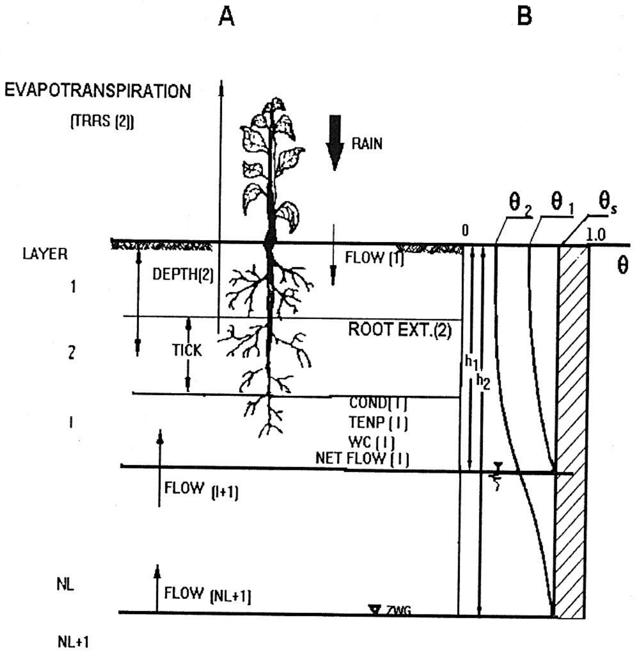


Fig. 2. Physical concept of A and B modulus of the soil profile moistening.

$$d_n = \sum_{i=1}^{n}\left(\theta_{1i} - \theta_{2i}\right) + \sum_{i=n+1}^{m}\left(\theta_s - \theta_{2i}\right)dw \qquad (9)$$

where: i - successive 5 cm thick layers, ($dw = 5$ cm), n - a number of 5 cm layers in the soil profile counted from the surface to a h_1 depth, m - a number of layers in the soil profile counted from the depth h_1 to h_2, (h_2 - depth of the water table in the soil for $\theta = \theta_2$).

The h_1 quantity is calculated on the basis of a numerically determined function (Fig. 3) [3]. The θ_1 value is obtained from the pF curves, whereas h_2 and θ_2 are given by the UGWTPN model. These values describe actual levels of ground water and the moisture level of the soil profile that we look for.

A complete set of documentation of the subroutine IRRDEC and its relation to the UGWTPN programme has been given in another paper [5]. A block diagram of subroutine IRRDEC is presented in Fig. 4. This programme also takes into account the influence of soil moisture variations $\theta(z, t)$ on plant growth. The second condition which is decisive for the irrigation performance will be economic evaluation of the irrigation efficiency consisting of calculations the ratio between crop yield losses caused by a drop of soil moisture and costs of the prospective irrigations.

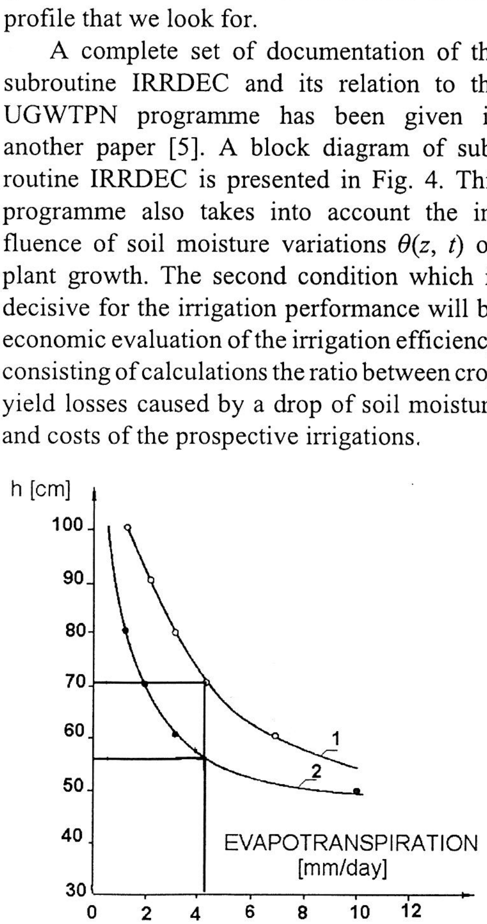


Fig. 3. Relation between the optimum ground water level and evapotranspiration for: 1 - peat soil, 2 - sandy loam [1].

RESULTS AND DISCUSSION

Solution for draine spacings system (model HZAR)

This model was used for the simulation of the efficiency of a drainage system based on the level of the ground water table, the water supply according to plant needs (grasses), and on the field workability, i.e., the accessibility of soil to field work and traffic operation. For some select simulations, let us assume that the drainage system can only drain water from the field. In the simulations considered pipe-drain spacings of $L = 5$, 10, 15, 20, 25 and 30 m, is considered with the following assumptions: pipe diameter is equal to 7.5 cm and the depth of the pipe is 100 cm (top of the pipe). Furthermore, let us assume that the root system is either uniform ($\mathrm{RDF}(z) = 1 = \mathrm{const.}$, $L_k = 60$ cm) or nonuniform, as in the studies by Olszta and Zawadzki [5]. Simulations were carried out for one growing season (April 1 - September 30) on a shallow heavy alluvial soil on silt.

A 'wet year' (666 mm of rainfall during the vegetative period, for instance in July - precipitation (P) = 164 mm, August - P = 153 mm, and in September - P = 118 mm) appeared to be crucial for the area under consideration.

The result obtained for the nonuniform rooting case are presented in Figs 5 and 6 in the example. Figure 5 illustrates position of the ground water table, h_{zw}, and the values of ET^{act}/ET^{pot} ratio. Figure 6 presents ranges of soil water pressure heads (h) at the surface.

The ratio of ET^{act}/ET^{pot} reached the minimum value, i.e., 0.31 for the drain spacing $L = 30$ m. Availability of water to plants at the nonuniform and shallower rooting depth ($L_k = 40$ cm) at a narrower pipe-drain spacing ($L < 30$ m) was slightly higher.

The conditions of accessibility for field operations would be worse for the uniform but deeper rooting system.

From this data it can be seen that soil moisture conditions in the soil profile will not be favourable for the rooting systems considered during the second half of the vegetation

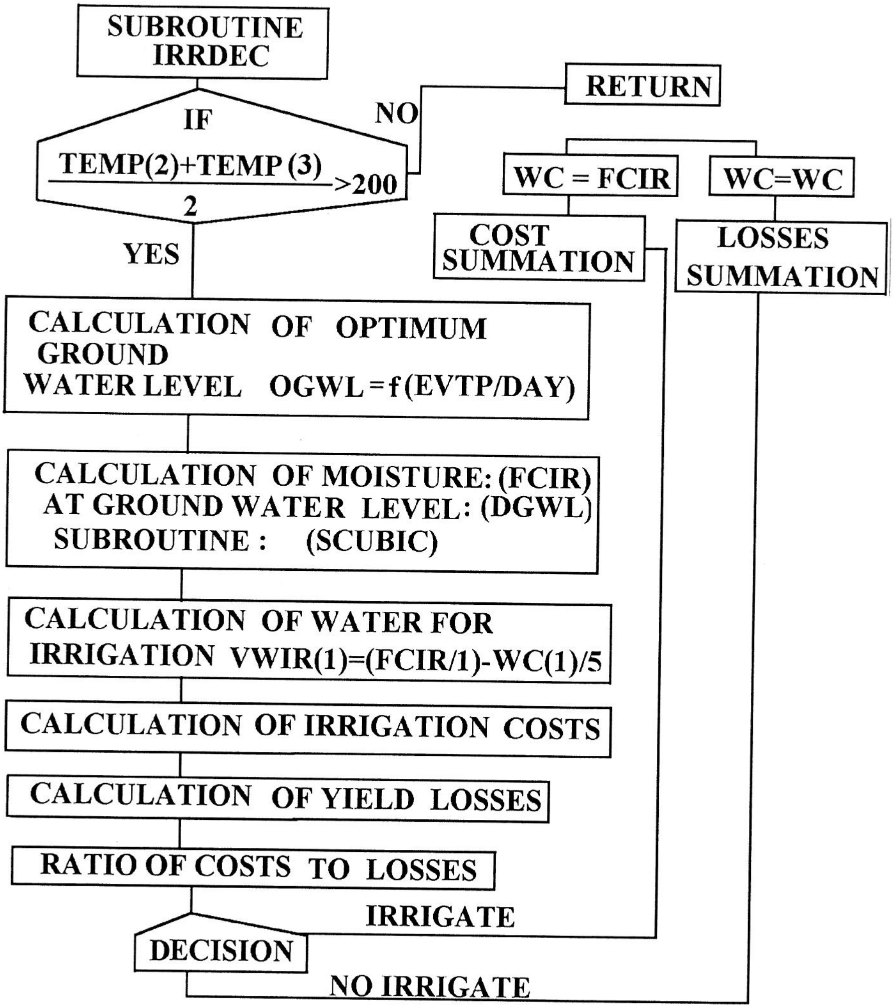


Fig. 4. A block diagram of subroutine IRRDEC.

period (starting from the end of July). Improvement can be obtained with deeper drainage and by growing plants with shallower rooting systems.

The results obtained by PHZLICZ code indicated that for the soil profiles under consideration the pipe drain spacing *L* would be about 10 m. This result obtained for $q = 10$ mm day^{-1} seems to be fair in the ligth of the solutions presented above by HZAR.

Solution for the period of long-lasting drought and irrigation PREDICTING (model UGWTPN)

The calculated results are presented in Fig. 7A for the drought period. The following parameters are given: a - rainfall distribution, b - dynamics of soil moisture tension at the layers 5 - 10, 25 - 30, and 55 - 60 cm deep (lines 1, 2, 3, respectively) for the initial state of the ground

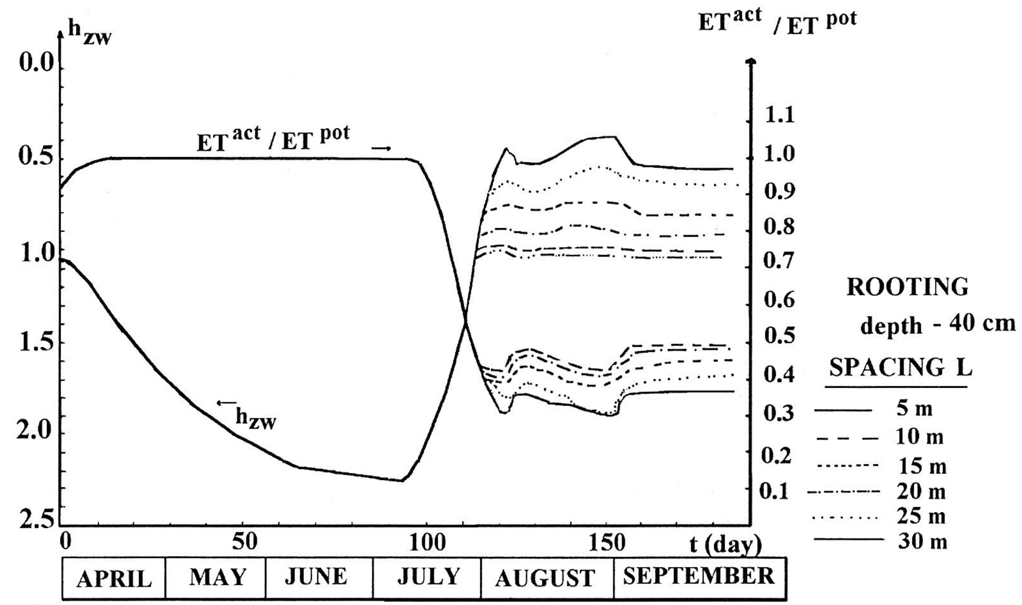


Fig. 5. The calculated position of the ground water level h_{zw} and the values ET^{act}/ET^{pot} for nonuniform rooting.

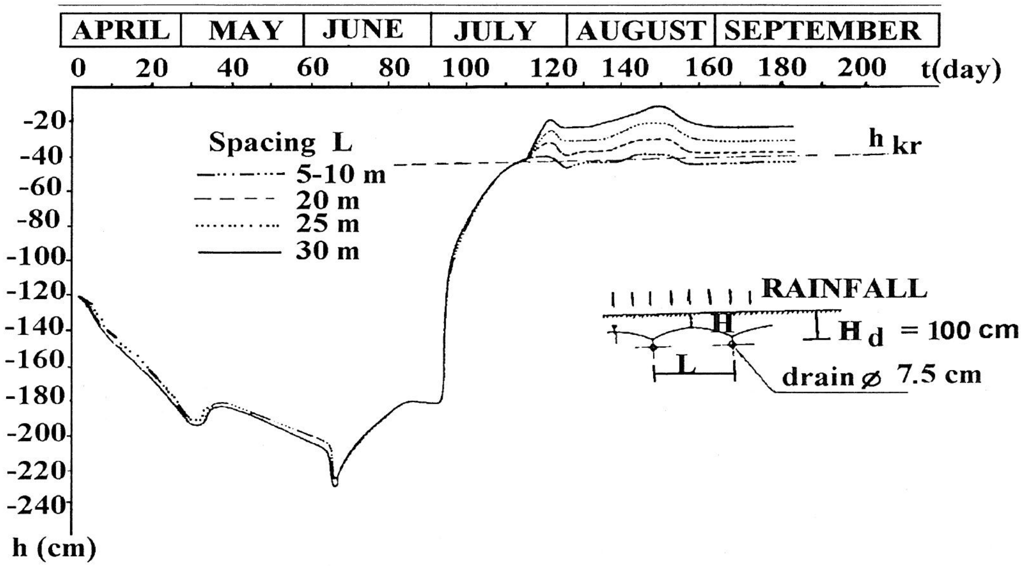


Fig. 6. The range of soil water pressure head at the soil surface (nonuniform rooting), h_{kr} - critical value of h at the depth 5-15 cm below the surface accessible for field operations.

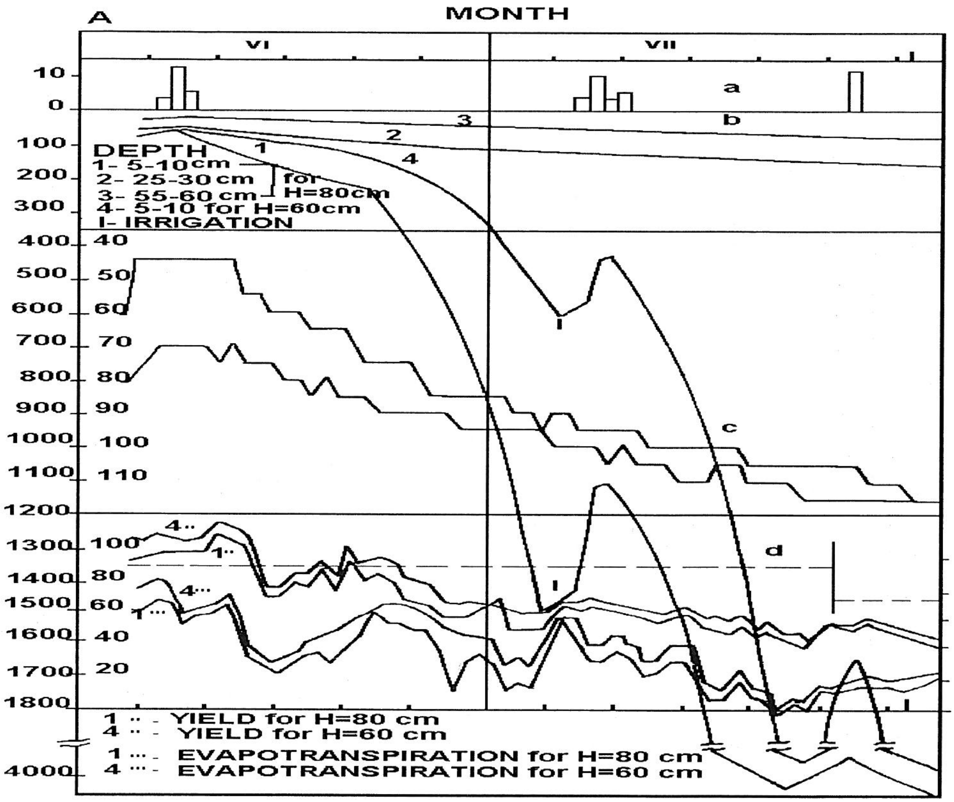


Fig. 7A. Rainfall (a), dynamic of soil moisture tension (b), ground water depth (c) and dry mass of yield and transpiration (d) for a long-term period of drought.

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 ground water status.

Significant differences between suction of the upper layer (5 - 10 cm) and deeper layers were observed. It proves that capillary rise cannot prevent a violent drying of the root zone and therefore, the suction at the 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 weather without rainfalls, whereas for the depth of *H* = 80 cm it was 1500 cm of the water column on the same day. Differences are equal to about 1000 cm and lasted till the end of the simulation period, i.e., till the August 5th. The difference of the initial (instantaneous) conditions of ground water (part c in Fig. 7B) at the beginning of the simulation process reached 20 cm, while at the end of the simulation it decreased to zero.

The results of calculations during 24 h growth of dry mass of hay and amount of water used for transpiration obtained from the simulation, are presented in Fig. 7A part d. 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} 24 h^{-1} but at the end of the calculation period that is on August 3. APG reached about 40 kg ha^{-1} 24 h^{-1}, i.e., two times less.

Similarly, to the former solution, calculation was carried out with application of capillary rise irrigation (Fig. 7B). It can be seen

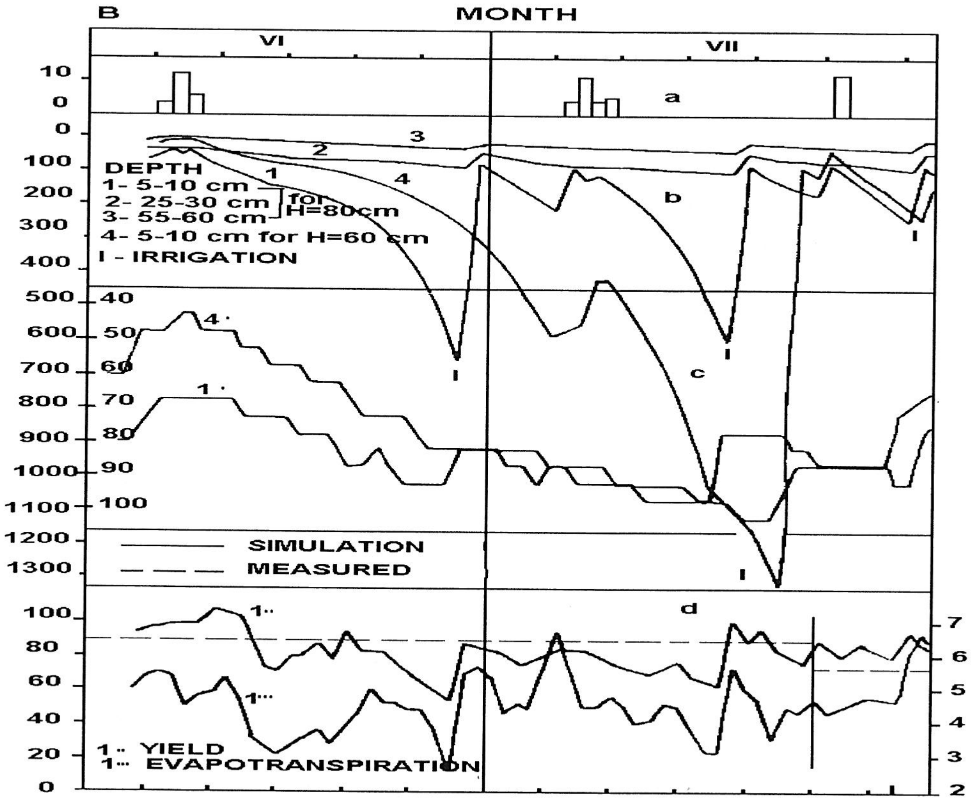


Fig. 7B. Rainfall (a), dynamic of soil moisture tension (b), ground water depth (c) and dry mass of yield and transpiration (d) for a long-term period of drought under irrigation (N).

that for 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 for the $H = 60$ cm on July 23.

The results of the grass growth calculations were presented in Fig. 7B part d, where line 1 presents the 24 h increases of the dry mass of hay with the $H = 80$ cm, dashed line presents the mean value of the 24 h increase for the second and the third swoth obtained from the experimental field of the Institute of Melioration and Grassland Farming at Sosnowica, in the climatic condition of 1983.

Prognosis of water relations for a long-term period of drought (as determined by the experiment) allows for economic solution of many important practical problems connected with irrigation.

CONCLUSIONS

Moistening of the soil profile is, as yet, the most important, and measured index characterising water relations in the soil. Plant yield was, also hitherto, only recorded in field conditions. Results of the investigations presented in this paper show a possibility of calculating the value of the $\theta(z, t)$ function and increases of the dry mass of meadow plants on the basis of climatic conditions and physical and water properties of the soil.

The results obtained under the project No. PBZ 31-03 allow us to solve a complex problem of water flow in the soil-plant system. A theoretical description including computer programmes aims at solving this problem. Basing on these results, we may conclude that these methods can be helpful in explaining field and agrophysical basis of soil and plant productivity.

REFERENCES

1. **Bohne K., Olszta W.**: Estimation soil water supply capacity under various conditions by simulation. Polish J. Soil Sci., Vol. XXV/1, 1-9, 1992.
2. **Feddes R., Kowalik P., Zaradny H.**: Simulation of Field Water Use and Crop Yield. PUDOC Wageningen, 1978.
3. **Olszta W.**: Investigation of dynamic the soil water, growth of grass and prediction of irrigation used numerical simulation (in Polish). Habitation Dissertation, Falenty, 1981.
4. **Olszta W.**: The prediction of irrigation using the mathematical modeling method. Zesz. Probl. Post. Nauk Roln., 281, 163-176, 1982.
5. **Olszta W., Zawadzki S.**: Influence of potential of water soil to growth of grass and transpiration (in Polish). Prace Kom. Nauk. PTG, 10, 91-99, 1987.
6. **Zaradny H.**: A method for dimensioning of sub-surface drainage in heavy soils considering the reduction in potential transpiration. Proc. Int. Sem. on Land Drainage. Helsinki, 258-266, 1986.
7. **Zaradny H.**: Mathematical methods of description and solution of water flow problems in saturated - unsaturated soils (in Polish). Works of Hydroengineering Institute, Polish Academy of Sciences in Gdańsk, 23, 367, 1990.
8. **Zaradny H., Maciejewski S.**: State-of-the-Art and research trends for flow processes and disporsion in water-soil-plant-atmospheric system (in Polish). Internal report of Hydroengineering Institute, Polish Academy of Sciences in Gdańsk. CPBP 05.03.01.2, 1986.