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PRINCIPLES OF AVAILABLE SOIL WATER DETERMINATION USING DYNAMIC APPROACH

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Abstract. This study concerns the determination of soil moisture content at field capacity (PPW) and at the point limiting biomass production (PHWR) as well as the relationships between water stress index (ISW) and evaporative demand of the atmosphere. The results obtained have shown that calculation of irrigation norms deciding upon the hydraulic parameters of irrigation networks should include a dynamic character of available soil water both at the designing stage and at the conditions of exploitation. Some problems of microirrigation, in which the role of soil water retention in water management is very important, are also discussed. Water retention might be especially important when using microsprinklers, while during drip irrigation such retention might even be harmful.

INTRODUCTION

Knowledge of water transport processes in soil profile and of the possibility of their forecasting constitutes a basis for correct selection of drainage network parameters as well as for rational water management in the conditions of plant production. From the practical point of view, a modern drainage system must ensure close to optimum air and water conditions in the rhizosphere of plants. A high level of plant production and limited available water require more and more precise and quick information on actual and probable reserves of soil water. Therefore, for needs of land reclamation practice more and more often mathematical models are applied using numerical solutions of the fragmentary differential equation of Richards or its developed transformations.

Since most traditional irrigation systems are characterized by a cyclic action, irrigation modelling usually embraces the description of both the water distribution process into plants' rooting zone and of its depletion due to evapotranspiration in inter-irrigation cycling. One of the most commonly used forms of Richards' equation for the irrigation modelling is the Fokker-Planck equation in the form:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial \theta}{\partial x}\right] + \frac{\partial}{\partial y}\left[D(\theta)\frac{\partial \theta}{\partial y}\right] + \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial \theta}{\partial z}\right] - \frac{\partial[K(\theta)]}{\partial z} - S(h, E, z, t) \tag{1}$$

where: θ= soil moisture, t = time, x, y = horizontal coordinates, z = vertical coordinate, $D(\theta)$= soil diffusivity, $K(\theta)$= hydraulic conductivity of soil, S = water uptake by roots, h = soil water potential, and E = possible transpiration.

In the case of a unidirectional flow process, i.e. wetting or drying takes place, the dependence of moisture θ on soil water potential h is univocal and thus:

$$\frac{\partial \theta}{\partial t} = \frac{d\theta}{dh} \cdot \frac{\partial h}{\partial t} \tag{2}$$

Taking into account that factor $d\theta/dt$ constitutes a differential water capacity

$c(h)$, which characterizes water retention changes caused by the change of water potential, and soil diffusivity ($D(\theta)$) was written by Buckingham in 1907 as

$$D(\theta) = K(\theta)\frac{dh}{d\theta} \tag{3}$$

Eq. (1) for unisize vertical flow can be expressed in the form:

$$c(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] + \frac{\partial K(h)}{\partial z} - S(h, E, z, t) \tag{4}$$

The above form of Richards' equation (Eq. 4) is commonly used for analytical as well as numerical solutions [1,5,10,22,25].

Because of the manner of water distribution during irrigation the solutions are considered in the form of Cartesian or cylindrical coordinates. For example, the microirrigation systems which are more and more often applied in agricultural practice can be considered a three-dimensional system (single, independent and point water source - dropwise); two-dimensional system (densely distributed linear water sources-deep and dropwise microsprinklers) and a one-dimensional system (density distributed surface water source - microsprinklers).

Because of the manner of water distribution, one can find in literature the solutions for stationary or non-stationary flows [2,3,13,14,16,19,21]. A very interesting solution of Eq. (1) for non-stationary flow has been presented by Warrick *et al.* [19,20]. For linearization of the flow equation (Eq. (1)), they introduced Kirchhoff's transformation:

$$\Phi = \int_{h_0}^{h} K(h)\,\partial h\,. \tag{5}$$

Raats [15] has named the value Φ as the matric flow potential.

The transformation (5) proposed by Kirchhoff was used by Klute in 1952 [11] and then by Gardner in 1958 [6].

Moreover, using the following equation given by Gardner [6]:

$$K(h) = K_S \exp(\alpha h) \tag{6}$$

where K_S is the filtration coefficient and α is an empirical coefficient characteristic of a given soil, and introducing Eq. (6) into Eq. (5), and then solving the integral when $h \to \infty$ Philip obtained [12]

$$K(h) = \alpha\Phi \tag{7}$$

Then Eq. (1) can be written in the form:

$$\frac{\partial\theta}{\partial t} = \nabla^2\Phi - \alpha\frac{\partial\Phi}{\partial z} - S' \tag{8}$$

where ∇^2 is Laplace operator and S' stands for source link.

Warrick and Lomen [19] used Eq. (8) for the description of stationary and non-stationary flow in both the Cartesian and cylindrical coordinate systems.

For stationary conditions, if $\frac{\partial\theta}{\partial t}=0$ then we obtain:

$$\nabla^2\Phi - \alpha\frac{\partial\Phi}{\partial z} - S' = 0 \tag{9}$$

and considering that $\frac{d\theta}{d\Phi} = \frac{\alpha}{k}$; $k = \frac{dK}{d\theta}$ then Eq. (8) for non-stationary flows can be written in the form:

$$\frac{\partial\theta}{\partial t} = \frac{k}{\alpha}\nabla^2\Phi - k\frac{\partial\Phi}{\partial z} - \frac{k}{\alpha}S' \tag{10}$$

Eq. (10) has been used to study the dynamics of soil moisture changes during drip irrigation while Eq. (4) has been used for numerical simulation of microsprinkling irrigation.

An irrigation system should fullfil three basic functions: it should supply water of a proper quality, of a required amount and in due time. The realization of these aims can be achieved using different techniques and strategies. The irrigation technique as well as financial constraints very often limits the possibility for applying the most adequate strategy from the view point of plant growth.

The problem of optimum soil moistening is extremely important because of its close connection with an energetic economy of the plant. Next, the energetic status of the plant depends upon the range of biomass increment. In conditions of water stress, the distribution of energy for the formation of the plants structure, for maintaining the equilibrium and for the crop yields is decidedly unfavourable. The effect of water stress on a plant's yield depends on its duration and intensity and the growth stage of the plant. Numerous studies have shown that even short-lasting water deficits can considerably decrease the crop yield, if they occur during a particularly sensitive time for the plant. For that reason, one should recognize that to obtain a high yield it is necessary to maintain the soil water potential in an optimum range.

The idea of unstressed water management can be realized by applying source and energy-saving techniques, such as micro-irrigation systems (microsprinklers, drip irrigation, deep-drip irrigation). These systems allow us to interfere precisely in soil moistening processes. Wetting the soil only occurs within a definite area tightly fitted to the plants' root mass distribution. Such a system ensures very safe water economy.

The course of irrigation and the dynamics of soil moistening during application of microirrigation depend on three basic factors:

(i) a group of environmental features including, for example, hydro-physical properties of the soil and the course of evaporative conditions;
(ii) constant elements imposed by the designer including, among many others, arrangement and construction of elements supplying water directly to plants as well as their location in relation to the terrain surface; and
(iii) irrigation technology which consists of, among other things, discharge from a single source, irrigation area, and the time of irrigation as well as time between irrigations.

Characteristic boundary states of soil moisture in connection with the plant and external conditions depend upon the magnitude of soil water resources in a dynamic state.

METHODS AND RESULTS

In conditions of cyclic irrigation, a very essential problem created is establishing the range of retention which can be depleted from the soil surface during inter-irrigation periods. At the time of designing the melioration system as well as during its exploitation, one should consider its dynamic character. The dynamic character of retention results from the course of external conditions, mainly atmospheric ones, which radically affect the plant's strategy in relation to water and energy economy.

In prognostic tasks which are most often considered on the basis of numerical modelling of water transport processes in soil profile, there is an absolute necessity to know the initial distribution of moisture in the soil profile, the description of the course of boundary conditions and the proper parametrization of the source link. To obtain the solution of Richards' differential equation, knowledge of soil parameters determined in an experimental way is also necessary. The parameters are the soil moisture in function of suction pressure $\theta(h)$, hydraulic conductivity in function of either moisture $K(\theta)$ or soil suction pressure $K(h)$, and the time course of the function of water uptake by the plant's root system $S(h,E,z,t)$. Because all of the processes occurring in the soil are thermodynamically irreversible and the soil is characterized by great time and spatial variability, as a porous medium, the parametrization of soil medium constitutes a serious technical and methodological difficulty which is clearly visible while determining its hydraulic conductivity at unsaturated state, $K(h)$.

The hydraulic conductivity of soil can be determined with various direct or indirect methods. Reviews on this subject have been presented by Klute [11], Żakowicz [25,28], Żakowicz and Brandyk [29] and Globus [7]. The studies on the course of *K*(*h*) function based on steady states, with the use of infiltration, dehydration and evaporation methods pointed out that they possess significant limitations when used for practical purposes. Basic limitations of the above methods are a relatively narrow range of the function being searched and a considerable time consumption. The elimination of these disadvantages is possible by applying the non-steady state methods where the use of non-inertia transducing pressure gauges is necessary. The need for a quick determination of the soil hydraulic conductivity has been taken into account by the authors in elaborating the measuring system for an automatic acquisition and transformation of soil physical parameters [17]. The above measuring system operates as a digital system in cooperation with the IBM XT computer which plays a steering function and processes the initial findings. The system enables the determination of the *K*(*h*) function within the suction pressure range from 0 to 800 hPa, in a period of about 5 days.

Mathematical modelling of water transport processes in the soil profile requires knowledge of the initial moisture distribution. The state of energetic equilibrium at which the sum of component potentials in the soil is constant has been most often assumed as the initial condition. It has also been commonly accepted that such a state is achieved by draining the soil, for two or three days, after formerly saturating it with water to the maximum water capacity. Studies on the course of moisture potentials during drainage of the soil pointed out that within such a short period, a state of energetic equilibrium is not achieved [8,9,23,26,27,30]. For example, after a three-day drainage of sandy soil (medium sand containing 9 % finesand, solid phase density - 2.61g/cm^3, and porosity 37 %) the potential obtained was equal to pF 1.74, while the potential corresponding to the state of a theoretical equilibrium was equal to pF 1.95. The difference between the two states was significant from the practical point of view as it reached 17 mm. The suction pressure values, expressed in pF units, after three days of drainage of undisturbed soil samples taken from the surface layers were as follow: for loose sand - 1.75, loose sand on the boundary of a slightly loamy sand - 1.72, light loamy sand - 1.78, strong loamy and silty sand lying on light silty loam - 1.81, and medium loam - 1.86. At the state of energetic equilibrium these pF values should reach respectively: 2.02, 1.95, 2.02, 2.02, and 2.02. Therefore, the differentiation of water reserves at the field water capacity for the root zone (50 cm) between the theoretical and steady state assumed from the practical point of view ranges from 5 to 20 mm.

Obtaining the solution of Richards' equation in respect to designing as well as prognostic problems is also conditioned by a proper parametrization of a source link *S*, which characterizes the intensity of water uptake by the root system of the plant. There is a direct connection between this problem and establishing the soil moisture level that inhibits the transpiration and consequently affects the crop yield. A commonly accepted average value of pF 3.0 or 3.5, which corresponds to the limiting biomass production point, can be a satisfactory approximation at the stage of designing the melioration investments. However, during the designing stage as well as during exploitation, this value should be established in relation to the assumed degree of safety of plant production. As a good index of it, one can consider here the ratio between the real and possible evaporation. Studies on the determination of the limiting biomass production point values (PHWR) on the basis of physico-physiological experiments have proved the very dynamic character of this feature. A detailed description of methods and results on the determination of the PHWR values has been presented by Żakowicz [26,27]. The exemplary values of the

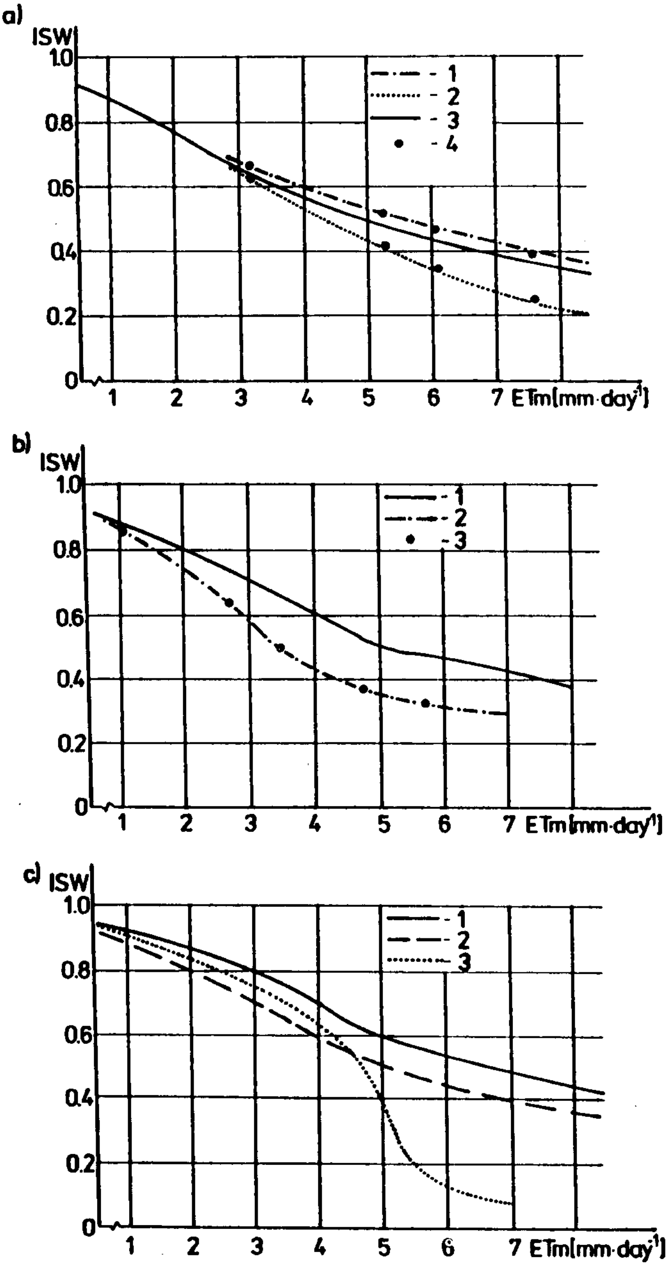

Fig. 1. Course of water stress index (ISW) in function of a possible transpiration ET_m for: a - grass (1 - $\theta_{ppw}^{pF=2.0}$, acc. to the study; 2 - $\theta_{ppw}^{pF=2.3}$, acc. to Doorenbos, [4]; 3 - experimental data); b - rye (1 - $\theta_{ppw}^{pF=2.3}$, acc. to Doorenbos; 2 - $\theta_{ppw}^{pF=2.0}$, acc to the study, 3 - experimental data); c - maize (1 - grown for grain, $\theta_{ppw}^{pF=2.3}$ acc. to Doorenbos; 2 - for green fodder, $\theta_{ppw}^{pF=2.3}$, acc. to Doorenbos; 3 - $\theta_{ppw}^{pF=2.3}$, acc. to Denmead' s lysimetric studies elaborated by Żakowicz, [27].

PHWR obtained for grasses on loamy sand at the evaporation levels equal to 8.5, 6.2, 5.3, 3.0, and 2.0 mm/day reached the following pF values: 230, 2.72, 3.08, 3.24, and 3.60, respectively.

On the basis of the experimental data the value of the so-called water stress index (*ISW*) can be established:

$$ISW = \frac{\varphi_{PPW} - \theta_{PHWR}}{\theta_{PPW} - \theta_{PTW}} \qquad (11)$$

where θ_{PPW} = soil moisture at field water capacity, corresponding for example to pF 1.8, 2.0 or 2.3; θ_{PTW} = soil moisture at the permanent wilting point.

The course of the *ISW* index obtained experimentally in the function of transpiration possible for grasses, cereals and maize on the background of the values suggested by FAO is presented in Fig. 1. Knowledge of the water stress index course in the function of transpiration allows us to determine the magnitude of net irrigation dose in the dynamic approach.

$$\Delta R \left[ET_{m}^{x} = WOD\, h\, (ISW) \right] \frac{Q_{j}^{PPW}}{ET_{m}^{x}} \qquad (12)$$

where $\Delta R_{ET_{m}^{x}}$ = the magnitude of soil water reserves at the possible transpiration ET_m equal to x mm/day (mm), *WOD* = accessible water content (%). $WOD = \theta_{PPW} - \theta_{PTW}$ for the layer being calculated, h = thickness of the layer being calculated, the centre of which is at j cm distance from the water table level (dm);$(ISW)\frac{Q_{j}^{PPW}}{ET_{m}^{x}}$ = value of the water stress index for a given ET_{m}^{x} and moisture θPPW for pF = log (j).

The course of the water stress index during numerical simulation of prognosis of the depletion of discretionary reserves of soil water allows us to describe properly the source link in Richards' equation and to calculate the maximum allowable time between irrigations (T_{max}). The exemplary variability course of the magnitude T_{max} for the profile with a deep ground water table (200 cm) in relation to possible transpiration ET mobtained by using computer simulation Eq. (4) is presented in Fig. 2.

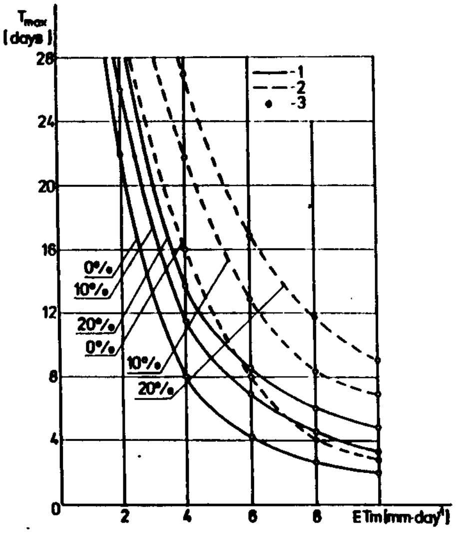

Fig. 2. Course of maximum times between irrigations (T_{max}) in relation to possible transpiration for different degrees of the grass yield increase and the amount of generally accessible water (WOD): 1 - WOD=50 mm; 2 - WOD=100 mm; 3 - points obtained from numerical computations of microsprinkling irrigation.

Numerical programmes elaborated by Warrick *et al.* [19,20], which allow us to solve the irrigation from point, linear or disc sources, with the permission of these authors have been modified and used with the IBM PC/XT computers. The programmes embracing both the two- and three-dimensional tasks were used in simulation experiments and verified on the basis of a physical model and on the lysimetric studies (Fig. 3). An exemplary distribution of potentials in soil obtained by numerical solution, for the case of a point source situated on the soil surface and having a rate of 113 and 240 cm^3/day cm in conditions of stationary flow, is presented in Fig. 4. The values of soil suction

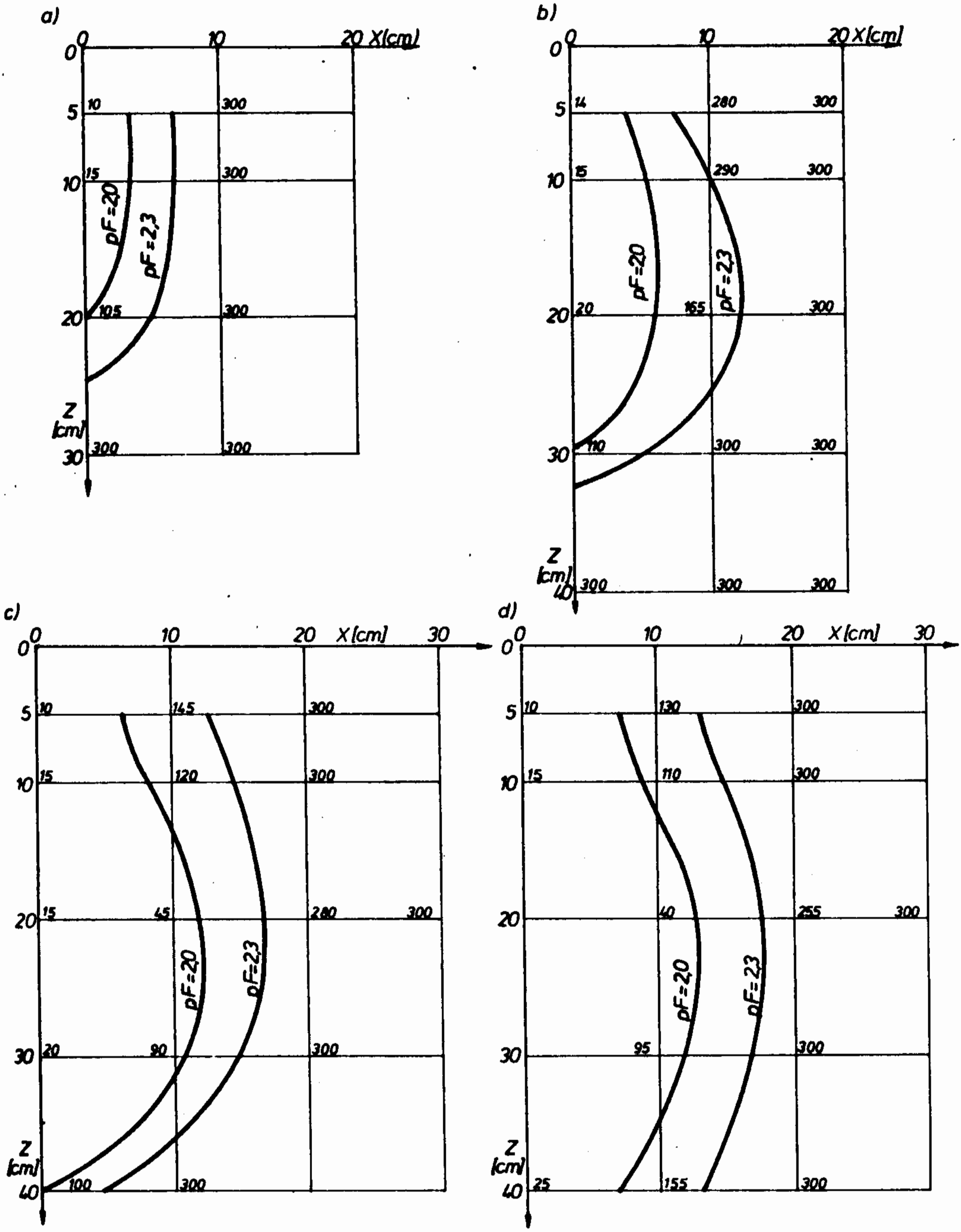

Fig. 3. Distribution of suction pressures h (pF=log/h/) obtained in the laboratory chamber filled with peat-bark mixture (with the rate of a single emiter 2.6 dcm^3/h) after different duration time of drip irrigation: a - t=15 min; b - t=40 min; c - t=1 h 30 min; d - t=4 h 30 min.

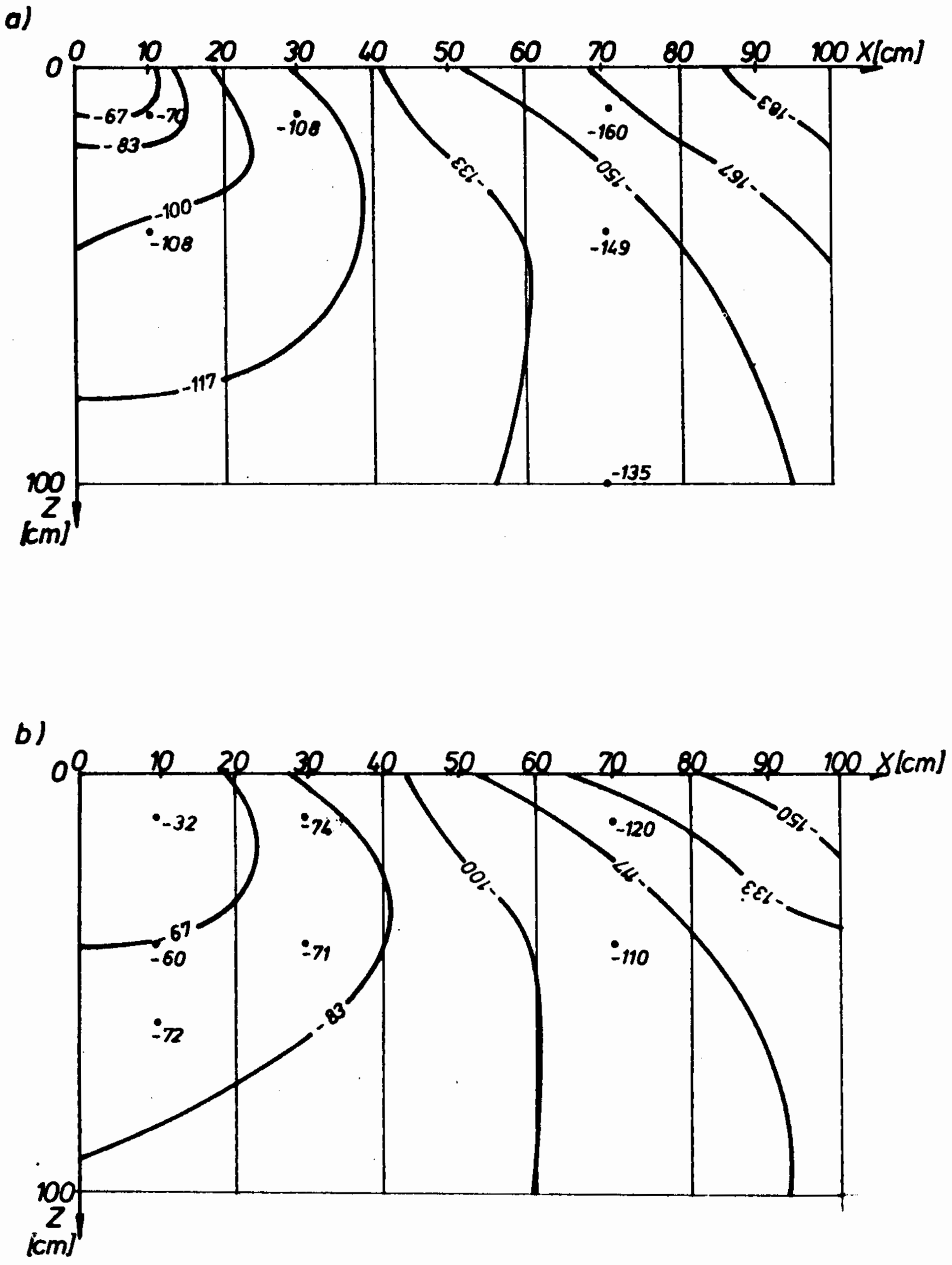

Fig. 4. Distribution of suction pressure values h (hPa) in light loam obtained from Warrick and Lomen's model, for steady state at the rate of line irrigation equal to: a - 113 cm^3/day cm; b - 240 cm^3/day cm; o$_{-32}$ - points in lysimetric chamber where the suction pressure values were measured.

pressure (*h*), measured directly in the lysimeter for the same magnitude of the irrigation line rate, are also given there. A comparison of the distribution of the *h* values obtained points to a great comformity of numerical calculations with the results of lysimetric studies.

CONCLUSIONS

1. The studies on the field water capacity, on the limiting biomass production point, and on the water stress index point out that the reserves of water easily accessible to plants have a dynamic character.

2. Considering the magnitude of disposable soil moisture reserves at the stage of designing and at the exploitation of a given melioration object as a constant, magnitude is inexact and in consequence it may lead to a decrease in crop yield.

3. In mathematical modelling of the irrigation processes a correct parametrization of the system of soil-plant-atmosphere continuum plays a particularly important role. Investigations on soil hydraulic conductivity have proved that the most effective results have been obtained by using the non-steady state method.

4. The application of microirrigations eliminates the discrepancies between the plant's strategy and technical possibilities of traditional irrigation systems.

5. By applying microsprinkling irrigations one can properly manage the water economy as the system saves both water resources and energy, providing that the magnitude of soil water reserves are exactly estimated in a dynamic way. The above has been confirmed by the investigations carried out under lysimetric and field conditions.

6. Managing the water during drip irrigation to a great extent limits the significance of soil retention. Mathematical models proposed by Warrick and Lomen for steady- state conditions during drip irrigation are correct and that has been confirmed by the study carried out on a ground model both in the laboratory and under lysimetric conditions.

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ZASADY OZNACZANIA PRZYSWAJALNEJ WODY GLEBOWEJ PRZY UŻYCIU PRZYBLIŻENIA DYNAMICZNEGO

Prowadzone badania dotyczyły ustalenia wilgotności gleby przy polowej pojemności wodnej (PPW) i punkcie hamowania przyrostu biomasy (PHWR) oraz przebiegu indeksu stresu wodnego (ISW) w zależności od zdolności ewaporacyjnej atmosfery. Uzyskane wyniki wykazały, że przy ustaleniu wielkości dawki polewowej decydującej o parametrach hydraulicznych sieci nawadniającej określanej zarówno na etapie projektowania jak i w warunkach eksploatacyjnych systemów nawadniających powinien być uwzględniany dynamiczny charakter dyspozycyjnych rezerw wilgoci glebowej. Podjęto również problematykę mikronawodnień, przy których udział retencji w gospodarowaniu wodą może być, jak w przypadku mikrodeszczowni bardzo istotny, a w przypadku nawodnień kroplowych znacznie ograniczony.