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SOIL SCIENCE

Water Permeability of Unsaturated Soils in the Arid Zone

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Abstract—The moisture permeability of sandy soils in the unsaturated moisture content regime has been studied. The intensity of moisture conductivity was measured at certain values of the current moisture. It is shown that the expansion of the range of unsaturated soil moisture makes it possible to determine the point of break in the monotony of the curve of simulation of moisture permeability due to the rupture of the capillary connection. The mathematical model of moisture permeability that takes into account the soil porosity is presented.

Keywords: soils, aeration zone, moisture permeability, hygroscopicity, moisture capacity

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The hyrdrophysical properties of soils that are currently assumed for the description of moisture transfer are generally constant. These are total moisture capacity (TMC), porosity (da), wilting point (WP), maximum hygroscopic moisture (MHM), maximum molecular moisture capacity (MMMC), filtration coefficient (K_f), etc. Soil scientists use these constants to describe the hydrophysical soil properties during the solution of problems of water flow under saturated and unsaturated conditions. However, to describe the water regimes of real soil-plant systems as agrolandscape elements, it is necessary to take into account their interaction with the atmosphere and the dynamic changes that occur in the process of their adaptation to the water balance regime, climate, anthropogenic impacts, etc. A.M. Globus noted an essential feature of this information base: "this enables one to describe the soil subsystem of the large soil–plant–atmosphere system as a dynamic organism with distributed parameters that is generally characterized by different values of moisture, moisture conductivity, and potential in different points of the soil profile at different points of time" [1].

While providing the qualitative description of the system, static constants cannot reflect the dynamics of hydrological processes in the soil and the density of moisture distribution in the aeration zone. In addition, they do not take into account the formation and development of the root system during water absorption. Therefore, the solution of one of the essential problems of agroecology, i.e., the optimization of water supply for agrocenoses, requires the spatial and temporal description of basic hydrophysical soil properties in the form of mathematical models with soil hydrophysical functions that describe the spatial and temporal pattern of moisture reserves and their motion, rather than with "dead" constants.

METHODS

The Federal Scientific Center of Agroecology, Russian Academy of Sciences, (the former All-Russia Research Institute of Agricultural Afforestation), has accumulated a large amount of experimental material on moisture transfer in different types of light soils that are characteristic of arid zones in the south of Russia [2–4]. Data are available on the rate of filtration flow, depending on the moisture of the above-capillary horizon [5], and on the gravity flow; sections of isolines with the same moisture (isopleths) and dynamics of the ground-water level have been constructed. This work used the data on the gravity flow in lysimeter no. 2; the hydrophysical properties of its soils are given in the table.

The use of Aver'yanov's model required the conversion of all the constants to volume percent. The water permeability was studied by the rate of gravity flow. The total moisture capacity was determined by porosity and the maximum hygroscopic moisture was experimentally determined on the basis of evaporation. These characteristics were used for calculating the relative moisture, $w_{rel.}$.

RESULTS AND DISCUSSION

The use of the numerical array that was obtained as a result of observations and combined into the database is hampered by the fact that the tabular data reflecting the hydrophysical processes require significant costs for the statistical processing, interpolation, extrapolation, regression analysis, etc. To perform the mathematical simulation and prediction of the situation in a specific region, it is more convenient to present the data from the lysimeters in the form of continuous functional relationships. These relationships, e.g., the relationships between moisture permeability, K_w, and moisture in the unsaturated soil can be revealed using a formal physicomathematical model or on an empirical basis, i.e., by matching the parameters of an appropriate continuous function using the regression analysis. The detailed semiempirical approach assumes the simplification of the results of formal simulation for practical application [1]. The objective of this work was to study the issues of hydrophysical support in the form of lysimetric data for simulating the dynamics of moisture transfer.

Lysimetric observations made it possible to assess the rate of the flow under different moisture conditions within the minimum moisture capacity (MMC), i.e., the WP. The closest relationships between the flow rate and moisture were recorded in those cases when the indices of moisture of the above-capillary film edge are used [6]. The functional relationship between these parameters can be described as the following relation: $K(w) = 0.0002e^{0.8w}$ at $R^2 = 0.89$, where $K(w)$ is the rate of the gravity flow, mm/h, and w is the gravimetric moisture, % [5].

Despite the high correlation, this interpolation is not physically substantiated and represents only a rather convenient approximation of water permeability as a soil moisture function. The water permeability of soils as a function should contain the hydrophysical characteristics corresponding to moisture flow conditions [1]. The physical characteristics include porosity, the filtration coefficient (K_f), the amount of pressed air, and maximum hygroscopicity; the flow conditions include viscosity, current moisture, external atmosphere pressure, temperature, etc. Under unsaturated conditions, the dependence of water permeability on moisture, porosity, and maximum hygroscopicity is observed. S.F. Aver'yanov [6] found the semiempirical relationship between these variables in the form

$$K_w = K_f\left(\frac{w - w_{mhm}}{\sigma - w_{mhm}}\right)^n = K_f w_{rel.}^n,$$

where σ is porosity, w is the current moisture, w_{mhm} is the maximum hygroscopic moisture, $w_{rel.}$ is the relative moisture, and n is the exponent of relative moisture that was fixed during the simulation of moisture flow in unsaturated soils with pressed air.

If we assume that the total moisture capacity can be determined by the dispersity of the medium or by porosity σ, the degree of soil saturation with moisture w in formula (1) is determined by condition $\sigma > w > w_{mhm}$ in this case. The semiempirical model (1) was developed on the assumption that the soil framework has a capillary tubular structure with an air space (pressed air) within the flowing water. In addition, the w_{mhm} value, or the moisture corresponding to the beginning of intensive water flow, is selected in the way that the relation (1) is true at exponent $n = 3.5$; i.e., w is an arbitrary constant in the data processing [6]. Therefore, we attempted to refine the concept of Aver'yanov for increasing the scope of the use of formula (1) in practice. In this work, the dependence of moisture permeability on moisture content was interpreted in terms of hydrophysical soil characteristics shown by the lysimeter. The work of Likhatsevich [7] shows that the maximum hygroscopicity and the exponent are functionally interrelated, which indicates the restriction of the simplified description of moisture flow [6]. Indeed, the model of Aver'yanov is based on the hydrodynamics of nonviscous liquid that flows along the regular system of linear tubular structures, i.e., capillaries without consideration of the heterogeneity of the structure of the soil framework requiring the stochastic approach to solving the problem of moisture permeability.

While clarifying the notion of MMMC among other hydrophysical soil characteristics, A.P. Likhatsevich concludes that the bound moisture can be subdivided into tightly bound moisture and loosely bound moisture, which, in turn, are differentiated by maximum hygroscopicity. The free water between the minimum (w_{mmc}) to total (w_{tmc}) moisture capacity is subdivided into perched water (between maximum molecular to minimum moisture capacity) and gravity water (at $w > w_{tm}$). The MMMC approaches the moisture in the rupture of the capillary connection, when the perched water loses its ability to flow during its evaporation and separates bound and free water. The author [7] notes that such notions as MMMC (w_{mmc}) and moisture in the rupture of the capillary connection (w_{mrc}) are synonymous, since they reflect the same process; therefore, he introduces the single notion of critical moisture (w_{cr}) that is determined by formula (1) using the variation in the parameter of initial fixed moisture (an analog of MHM). Different regimes of moisture transfer in the aeration zone were simulated from the minimum moisture content to total saturation w_{tm} [7]. For this purpose, we constructed diagrams of dependences of the exponent n in formula (1) $n = f(w)$, which show the nonlinear connection with the "break point" at $w = w_{cr}$. As a result, we obtained the threshold value of moisture (w_{cr}) that corresponds to the point of rupture of the capillary connection.

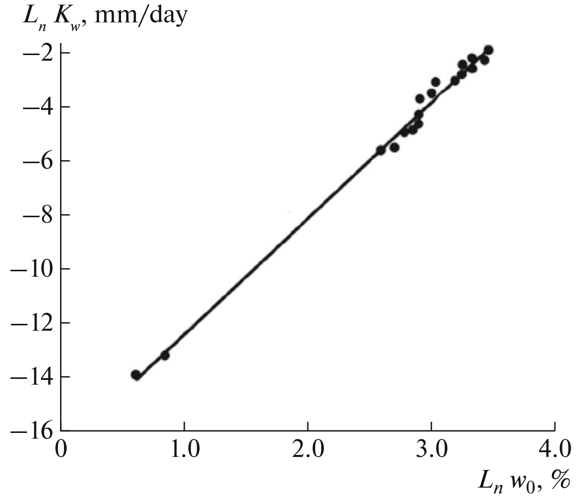

Fig. 1. Dependence of moisture permeability, Kw, on the relative soil moisture, $w_{rel.}$, shown by lysimeter no. 2; approximation by the exponential function $K(w_{rel.}) = 90.021\ w^{4.1}$; hydrophysical characteristics: w_{tmc} – 0.41, w_{mmc} – 0.21, w_{mmmc} – 0.14, w_{mhm} – 0.12 cm^3/cm^3.

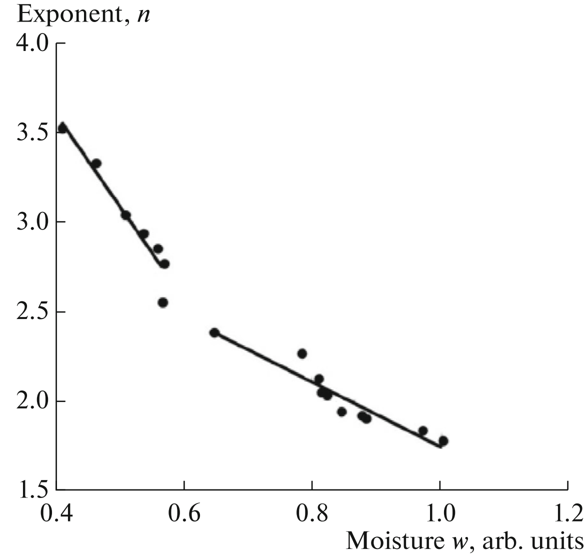

Fig. 2. Dependence of the exponent n on the current moisture w of soil shown by lysimeter no. 2; the moisture varied from w_{mhm} to w_{mmc}, cm^3/cm^3.

The critical moisture separates the bound and free water by the following quantitative relation: $w_{mmmc} = w_{mrc} = w_{cr}$. Therefore, the critical point means the differentiation between the bound and free water and is equal to the MMMC [7].

Figure 1 provides the experimental data on water permeability that were obtained in our work and shows the regression curve in the form of the exponential function (1). It should be noted that, despite the close approximation by the exponential function, the exponent $n = 4.1$ differs from the empirical curve [5] $n = 3.5$. The figure shows a sufficient adequacy of the exponential dependence. However, the exponent is not equal to 3.5, as suggested by Aver'yanov, who proceeded from the pressed air concept.

In formula (1), the author assumes the uncertainty in the selection of w_{mhm} values in the approximation of the semiempirical model (1). Therefore, if we assume, a priori, the adequacy of expression (1) for describing the dependence of moisture permeability on moisture content, the porosity m and maximum hygroscopicity w will be free parameters. The assumption was tested by a numerical experiment to reveal the dependence of the exponent n on the moisture content $n = f(w)$ at constant m and w_{mhm} values. Figure 2 presents the diagram that reflects this dependence at da = 0.41 and $w_{mhm} = 0.12$. In this case, only the current moisture changes, which, in our view, is due to the presence of critical moisture [7] that coincides with the moisture in the rupture of capillaries. At $w \approx 0.6$ of total moisture capacity, the monotonous trend of the curve, $n = f(w)$, is disturbed and, hence, the qualitative pattern of moisture transfer changes.

Therefore, the moisture flow in unsaturated soils can be described by the following algorithm: first, the water in the form of film moisture flows in the pore space by the mechanism of perched moisture and, upon reaching the critical value, begins to flow by the gravity mechanism under the effect of its own weight, when the moisture is between the MMMC and TMC. Since the values of these indices are not interrelated and there is the notion of moisture in the rupture of the capillary connection, under which the perched moisture loses its capability for free flowing, the resulting anomaly of the curve behavior, $n = f(w)$, at $w = 0.6w_{mmc}$ can be presumably explained by the rapture of the capillary connection. This result is in agree-

Granulometric soil composition

Layer depth, m	Density, g/cm^3	Content of physical clay, %	Hydrological constant, %		
			MHM	MMC	WP
0–1.0	1.5	5.0	0.65	6.0	1.0
1.0–2.2		1.0	0.40	5.0	0.6

ment with the critical value of moisture [7] that separates bound and free water.

The lysimetric measurements of the gravity flow reflecting the moisture permeability of soils make it possible to obtain valuable information on moisture transfer regimes in unsaturated media. The notion of critical moisture capacity is applicable for practical purposes during the irrigation of agricultural crops to determine the boundary between bound and free water. The consideration of the mechanisms of moisture flow in pressed air media is important in organizing irrigation agriculture and optimizing water resource utilization regimes.

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