Extreme Moisture Regime as the Main Limiting Factor of the Fertility of Salt Affected Soils

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The low fertility and agricultural utility of salt affected soils are, in most cases, closely related to their unfavourable physical and hydrophysical properties, their extreme moisture regime. This holds particularly true of heavy-textured alkali soils, because the interactions between soil colloids (especially expanding clay minerals) and the alkaline soil solutions containing a high amount of Na^+ result in radical changes in the moisture regime of the soil and consequently in mass and energy transport and transformation, thus creating a special, extreme soil ecological environment for native vegetation and agricultural crops [1, 2, 5, 7, 8, 17, 22, 23, 25].

These phenomena are briefly summarized in the present paper and, based on their analysis, some conclusions are drawn on the possibilities for up-to-date regulation of the moisture (and substance) regime in salt affected soils, which is the precondition of successful amelioration.

Water balance of areas and soil profiles

The main factors of the soil moisture regime (water balance of a soil profile) are schematically illustrated in Fig. 1. [26]. The general water balance equation for an area can be written as follows [13, 30]:

$$\Delta S = [P + I + R_i + U_i + G_i] - [IN + E + T + R_0 + U_0 + G_0] \qquad (1)$$

where:
- ΔS = water storage within the soil
- P = atmospheric precipitation
- I = quantity of irrigation water
- R_i = surface runoff into the area
- U_i = filtration within the unsaturated zone into the area
- G_i = groundwater flow into the area
- IN = interception (direct evaporation from the leaf surfaces)
- E = evaporation
- T = transpiration
- R_0 = surface runoff away from the area
- U_0 = filtration within the unsaturated zone away from the area
- G_0 = groundwater flow away from the area

The water balance for a soil profile can be interpreted in the following way:

$$\Delta S = [F_s + C] - [F_g + A] \tag{2}$$

where: ΔS = see above
F_s = infiltration into the soil
C = upward capillary flow from the groundwater to the overlying horizons
F_g = infiltration into the groundwater (through the soil profile)
A = quantity of water taken up by the plants

The rise of the water table (G_r) increases, while the lowering of the water table (G_s) decreases the quantity of water that can enter the soil profile from the groundwater (C).

The necessity, possibilities, and conditions for the various techniques of agricultural water management and soil moisture regime control are determined not only by the climatic conditions and the requirements of the cultivated crops, but also by the hydrophysical properties and moisture regime:

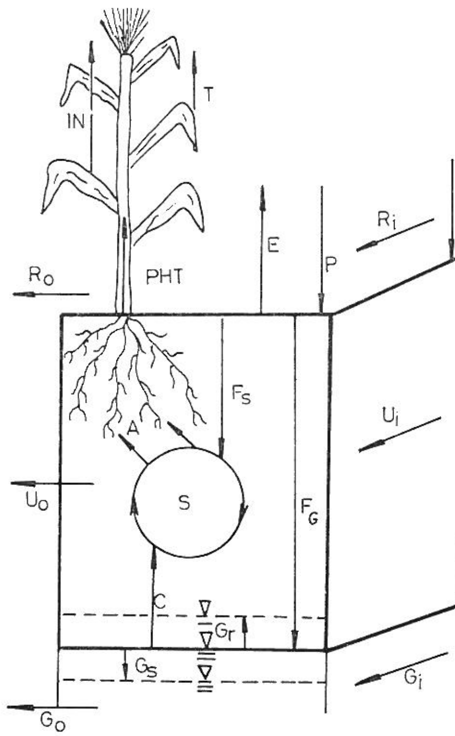


Fig. 1

Factors of soil moisture regime (for explanation see the text) PHT = physiological water transport within the plant; S = water storage within the soil; P = atmospheric precipitation; I = quantity of irrigation water; IN = interception (direct evaporation from the leaf surfaces); R_i = surface runoff into the area; R_0 = surface runoff away from the area; U_i = filtration within the unsaturated zone into the area; U_0 = filtration within the unsaturated zone away from the area; G_i = groundwater flow into the area; G_0 = groundwater flow away from the area; E = evaporation; T = transpiration the water management of the soils. The main factors of this are the depth, thickness and sequence of the various horizons within the soil profile between the soil surface and the groundwater table, as well as their hydrophysical characteristics: the quantity, status, chemical composition (concentration and ion composition) of soil moisture and also its vertical and horizontal movements (Fig. 2). For an exact and accurate characterization of the water management of the soil, it is necessary to have quantitative information on the above mentioned parameters, as well as on their spatial distribution and dynamism in time, on the influencing factors, their mechanisms and boundary conditions [24, 34].

The above mentioned factors determine the quantity of water available for plants in a certain area at a given time, and affect the conditions for the various agrotechnical measures.

The influence of salinity—alkalinity on soil moisture regime

Soil salinity—alkalinity exerts considerable influence on the

- mineralogical status (degradation, destruction and formation of clay minerals, orientation of clay particles, etc.) of the soil;
- rate of hydration and dispersion;
- swelling—shrinkage—cracking phenomena;
- arrangement of primary particles, shape, size and stability of soil micro- and macro-aggregates, structural elements, consequently the pore-size distribution;
- factors of soil moisture regime: spatial (vertical and horizontal) and time distribution of moisture content, moisture potential and moisture movement (vapour transfer, saturated and unsaturated flow, etc.) [25]. The interactions are summarized in Fig. 2.

The main soil factors limiting the optimum (adequate and continuous) water supply of plants can be divided into three major groups:

- limited water storage capacity
- cracking (swelling—shrinkage phenomena)
- low availability of soil moisture.

These factors are schematically illustrated in Figs. 3, 4 and 5, respectively [3, 10, 17, 20, 22, 25, 27].

Limited infiltration and saturated hydraulic conductivity

In the case of surface crust (cemented by Na-salts, gypsum, $CaCO_3$, etc. or compacted by improper soil management) or a compact soil layer (various hardpans; horizons cemented and compacted by accumulation of inorganic colloids, clay, exchangeable Na^+, etc.) near to the surface, not only the root penetration is impeded, but the infiltration of water into the soil is also limited which create an extreme moisture regime. The very low infiltration rate results in oversaturation and aeration problems (decreasing the availability of plant nutrients, causing anaerobic biological processes, unfavourable reduction, etc.) in a shallow wetting zone, in temporary water-logging after rainfall or irrigation, and in considerable evaporation losses and surface runoff (→ lateral erosion). The water storage capacity of this shallow wetting zone is very low, thus it can only satisfy the water requirements of plants for a short period. This is the

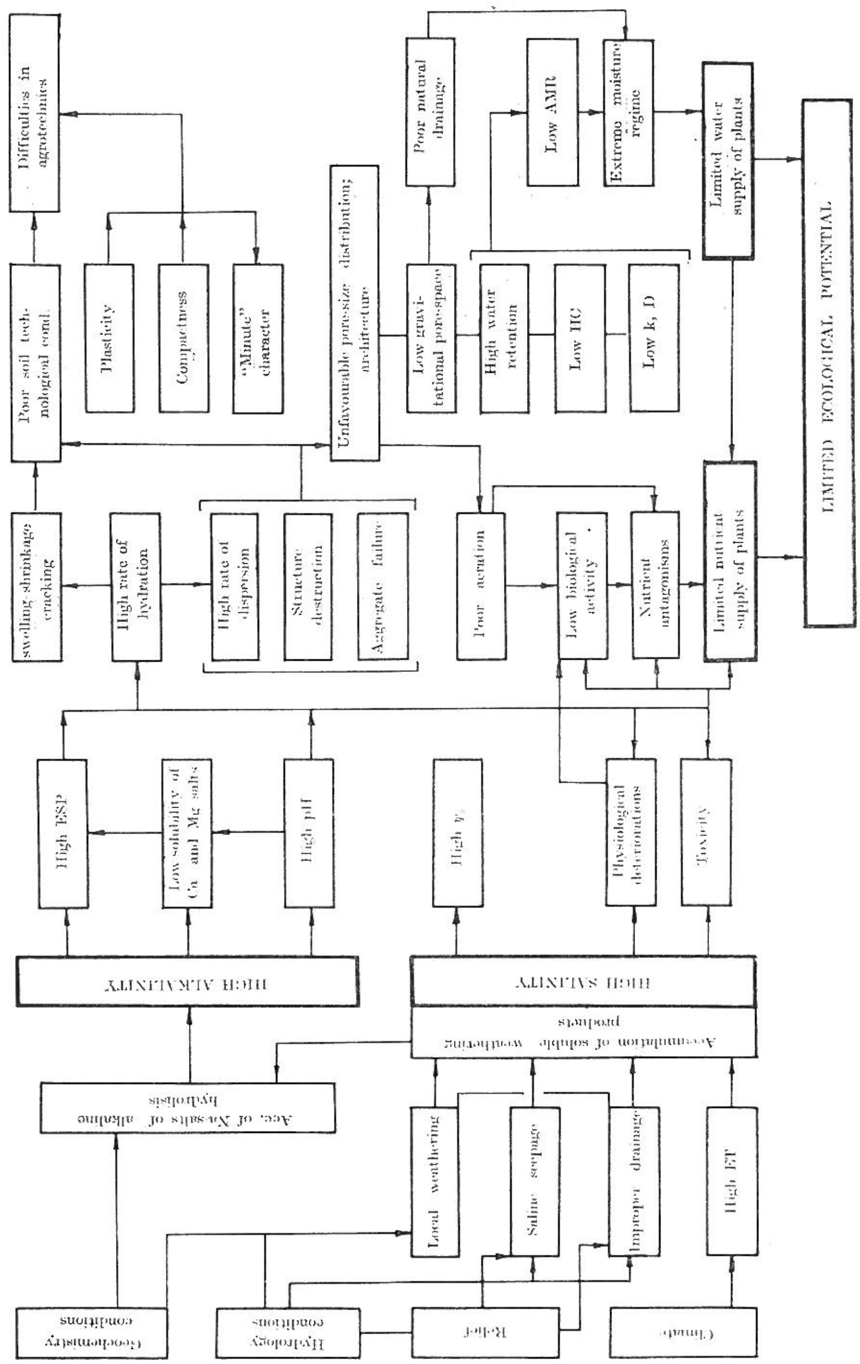


Fig. 2
The main factors of salinity and alkalinity in soils and their influence on the ecological potential

main reason for the special drought-sensitivity of heavy-textured alkali soils even under irrigated conditions (Fig. 5).

The infiltration rate as a factor of time is given for two Hungarian salt affected soils (heavy-textured, highly Na^+-saturated Hortobágy solonetzes) in Fig. 6 [7]. It can be clearly seen that after a fairly short "active" period (filling up the free pore-space; filtration through the open cracks) the *IR* radically decreases and is stabilized at a very low level ($\approx$ very low saturated hydraulic conductivity).

After the saturation of the soil pores by water (or by the filtrating liquid) conductivity can be theoretically characterized by a single value ($K =$ cm/day) which depends primarily on the geometry of the soil pores and on pore-size distribution. Under natural conditions this is true only for soils with good structure and aggregate stability, for structureless coarse sands, etc. In other cases — especially in salt affected soils — during the filtration of the soil solution, mechanical compaction or solid-liquid phase interactions take

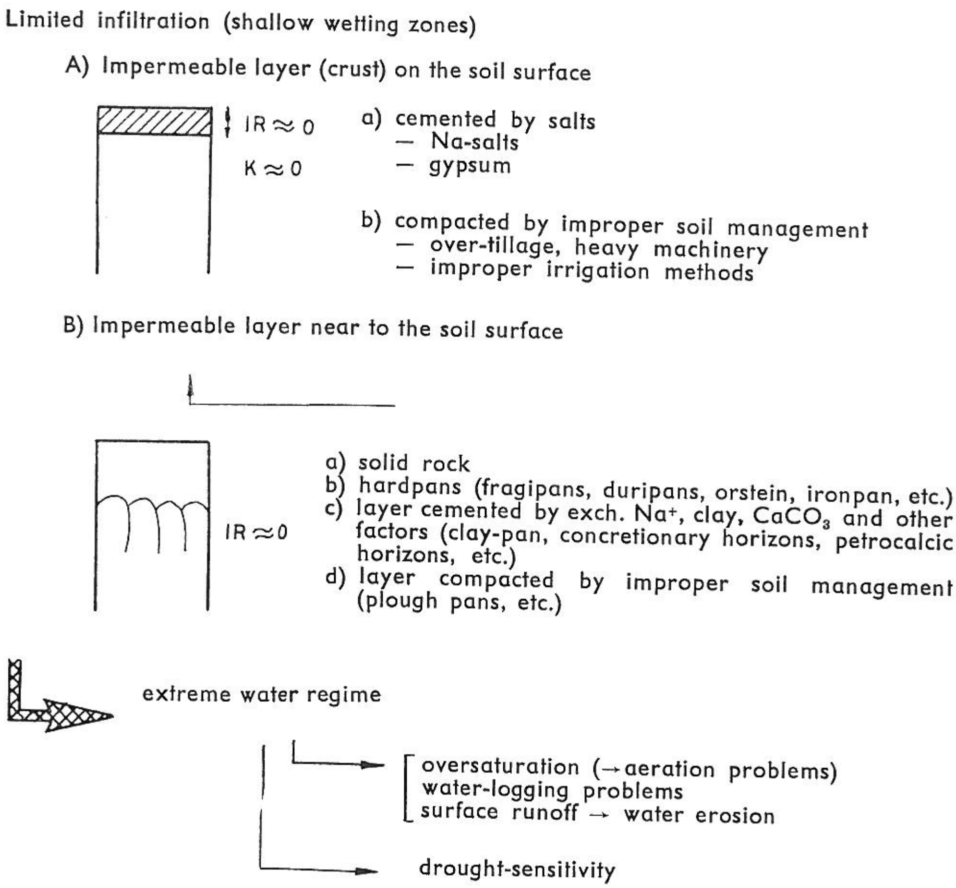


Fig. 3

Soil factors limiting optimum water supply of plants. I. Limited water storage capacity the particles, which are not cemented or bound together, will be dispersed again. Consequently, the hydraulic conductivity (K) of highly saline soils (e.g. 0—3 cm top-horizon of the soda-solonchak) is relatively high, but during leaching the electrolyte concentration of the permeating soil solution falls below the "threshold" concentration. So the flocculating effect of high salinity becomes negligible and the physical consequences of high Na^+-saturation manifest themselves more expressly, as can be seen in Fig. 7. Here, besides the

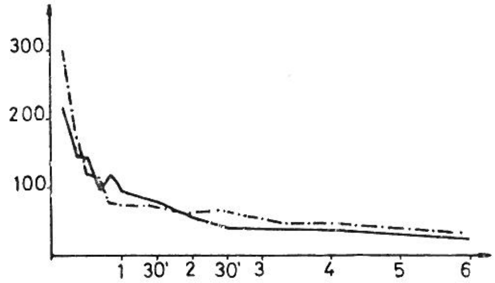


Fig. 6
Infiltration rates (mm/hours; hours) of two Hungarian salt affected soils

changes mentioned in (*i*), an intensive swelling takes place due to the high hydration of absorbed Na^+ ions and expanding clay minerals. As a consequence of swelling, bulk volume and total pore volume increase and bulk density decreases with increasing Na^+-saturation. At the same time, the saturated hydraulic conductivity sharply decreases, as is shown in Fig. 7. This phenomenon is quite contrary to the expectations one may have from the Kozeny-Carman equation or similar ones which indicate that conductivity is proportional to porosity. Here — due to the high rate of dispersion and hydration — a special pore-size redistribution takes place and a considerable part of the water exists in fine pores, bound strongly to the solid particles (sorption, interlayer water, etc.). Consequently, it cannot be removed below a certain hydraulic gradient and shows a special "semi-solid" state. In extreme cases this semi-solid state "dead water" completely fills the pores and due to this "clogging" hydraulic conductivity can be as low as zero. Another consequence of the previously mentioned pore-size redistribution is non-Darcian flow behaviour [3, 27]: conductivity increases with an increasing hydraulic gradient, because in such cases an increasing part of the "semi-solid" water can participate in the flow process. This phenomenon is illustrated schematically in Fig. 8.

In $NaCl-Na_2SO_4$ type salt affected soils (salinization caused is by neutral sodium salts) the influence of relatively low Na^+ saturation can be counterbalanced by the flocculating effect of high salinity, consequently, these soils have relatively better permeability. By contrast, the hydraulic conductivity of heavy-textured, soda-salinized alkali soils decreases sharply with an increase in ESP (Fig. 7).

Because of the extremely low vertical and horizontal saturated hydraulic conductivity of heavy-textured alkali soils having a high swelling clay content, natural drainage is very poor and the possibilities of leaching are limited. Consequently, their formation processes, caused by sodium salts capable of alkaline hydrolysis, are almost irreversible.

The key problem in the agricultural utilization of heavy-textured soda soils — besides the control of saline groundwater — is the improvement and maintenance of sufficient permeability to permit salinity control and reclamation. For the amelioration of these soils leaching (irrigation and drainage) alone is not sufficient because it may result in a reverse effect (diluted solutions → decrease in permeability). Therefore, leaching has to be combined with the application of chemical amendments (gypsum, etc.) and proper tillage practice. These complex ameliorative measures are rather expensive, therefore in the case of these soils the prevention of salinization and alkalization has special importance and sometimes it is the only way (at least the only economic way) to maintain soil properties within the range permitting proper agricultural production [6, 8, 9].

The extremely low infiltration rate and hydraulic conductivity of heavy-textured alkali soils are among the reasons responsible for the development of their particularly heterogeneous microrelief and their special vertical and horizontal micro-distribution patterns. Limited infiltration results in a characteristic micro-runoff even after moderate rainfall. It induces a certain kind of micro-erosion and, at the same time, increases the extreme differences between the dry (→ drought sensitive) higher spots and the moist, wet, sometimes water-logged lower ones. Because of the limited water storage capacity of the soils, the mosaics of these "too dry" and "too wet" small size spots show great spatial (horizontal and vertical) and time variations, which makes the ecological environment really extreme, tolerable only for some special xerophytic—halophytic native plant communities (Fig. 9).

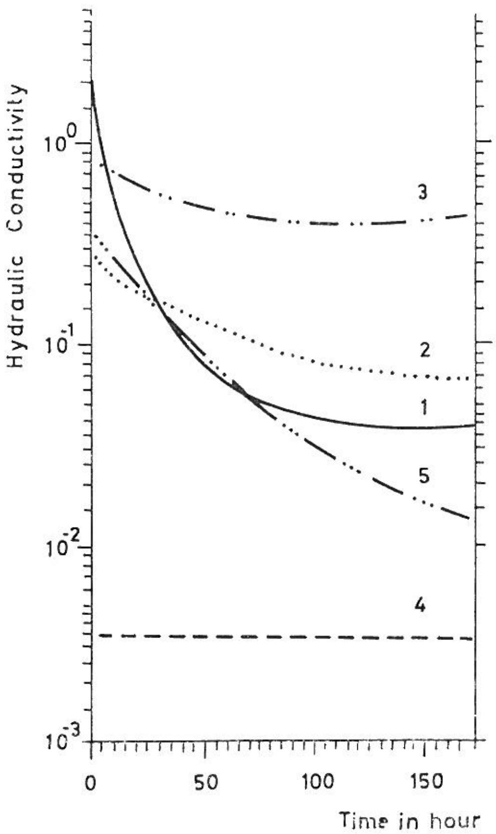


Fig. 7
Permeability curves (saturated conductivity changes in time) of various horizons of salt affected soils (K = cm/day)

Cracking (swelling—shrinkage phenomena)

Crack formation in swelling clays causes another water problem in heavy-textured alkali soils (Fig. 4). When the soil is dry, some of the rain or irrigation water flows through the open cracks directly to the groundwater. These "filtration losses" diminish water storage in the soil, decrease water use efficiency and, at the same time, may result in a rise of the water table, which may be accompanied by such unfavourable processes as water-logging, oversaturation (in the case of a high water table) or secondary salinization and alkalization (in the case

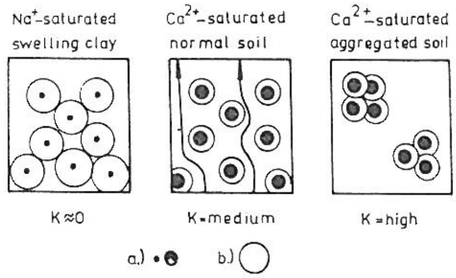


Fig. 8
Schematic diagram of non-Darcian and non-Kozeny-Carman flow behaviour. *a)* Solid particles; *b)* Strongly bound ("semi-solid state") water around solid particles

of a shallow, stagnant, saline groundwater). During dry periods the soil may dry out deeply through the deep and wide cracks (→ considerable evaporation losses). In rainy seasons the clogging cracks impede deep percolation and result in problems similar to those mentioned above.

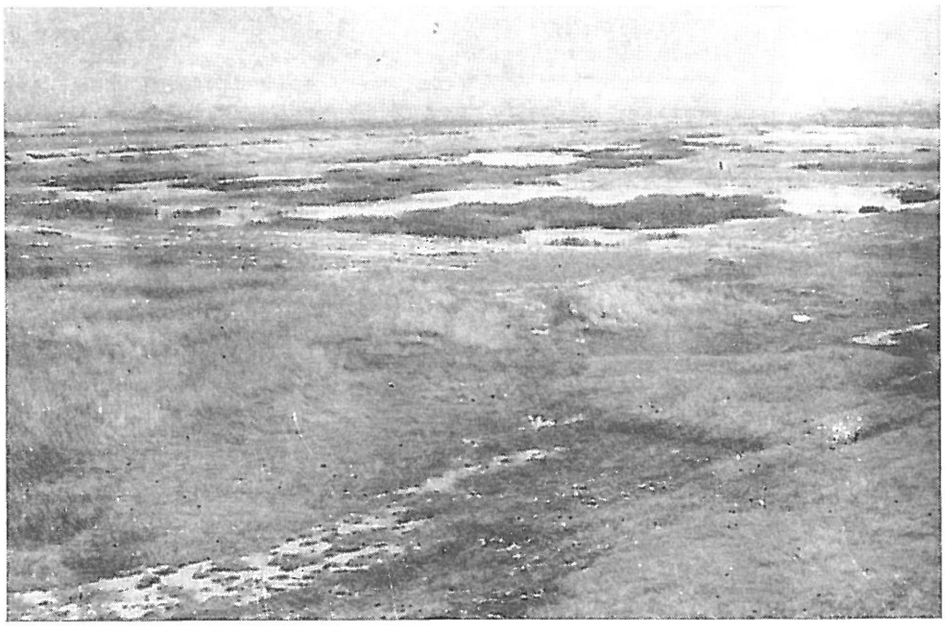


Fig. 9
Heterogeneous, mosaic-like surface of a salt affected soil

Low availability of soil moisture

As can be seen in Fig. 5, the low availability of soil moisture in salt affected soils may be the consequence of the following factors:

- high matric suction
- high osmotic potential
- low transmissibility coefficients (unsaturated conductivity, k; diffusion rate, D).

pF curves (expressing matric suction – moisture content relationships) have special significance in the exact and quantitative characterization of the moisture status and hydrophysical properties of soils [3, 4, 14, 18, 27, 28, 31].

The influence of salinity-alkalinity on the matric potential (ψ) is a complicated phenomenon directly or indirectly related to the changes in the soil physical status due to the relationships between the solid and liquid phases of the soil.

The alkalization (high Na^+-saturation) of soils, especially of heavy-textured soils having a high swelling clay content, causes increased hydration, swelling, dispersion of soil colloids, aggregate and structure destruction, and clogging of macropores, i.e. significant, sometimes radical changes in pore-size distribution: pore-size and macropore volume decrease, while micropore volume increases. These changes are clearly reflected by the water retention curves.

In Table 2. the data of a laboratory model experiment are summarized. The influence of various Na-solutions (0.05N, 0.1N and 0.5N NaCl and Na_2CO_3) on the water retention of two soils was studied: No. 169.: Pseudomyceliar chernozem, calcareous loam, Transdanubian loess plateau, Érd; No. 349.: Meadow chernozem, slightly calcareous clay loam, Transtisza loess plateau, Törökszentmiklós.

The main properties and particle-size distribution of these soils are given in Table 1.

The influence of a neutral sodium salt (NaCl) proved to be insignificant in the concentration range studied (low Na^+-saturation). 0.5N NaCl caused a moderate swelling (pF 0) and a slight increase in the wilting percentage (pF 4.2).

Due to the effect of a sodium salt capable of alkaline hydrolysis (Na_2CO_3), as the concentration increased (increasing ESP) the water retention also increased within the whole suction range, thus resulting in higher "total porosity" ($\varphi = 0$), "field capacity" (pF 2.3–2.7) and "wilting percentage" (pF 4.2). However, due to the large pore $\rightarrow$ fine pore pore-size redistribution (aggregate destruction, dispersion, peptization, hydration, swelling, etc.) the gravitational pore-space decreased (Table 2). Consequently, in such cases the effectiveness and efficiency of normal drainage methods are rather limited. These changes are expressed more clearly in the Törökszentmiklós clay loam than in the Érd loam.

The available moisture range (AMR), calculated as the difference between "field capacity" (pF 2.0–2.7) and "wilting percentage" (pF 4.2), increased with ESP, which is quite contrary to the classical explanation of the inadequate water supply of plants in alkali soils and proves the opinion of various authors, that in such cases the main limiting factor of the availability of soil moisture is not the low AMR, but the transport coefficients (capillary conductivity, k, and diffusivity, D); the flux from the wet soil to the plant roots — in spite of the

Table 1

Main properties and particle-size distribution of the studied soils

Properties		Soil (Code No.) 1	2	3	4	5	169	349
Horizon		1st	2nd	6th	B_1	B_2	*A*	*A*
Depth, cm		0—4	4—16	90—110	3—15	15—25	0—20	0—20
pH	I	9.1	9.0	8.2	7.9	8.3	7.7	6.9
	II	9.2	0.2	8.5	8.3	8.8		
$CaCO_3$ content, %		9.6	13.3	28.2	—	—	7.1	1.2
Total salt content, %	I	1.20	0.45	0.17	0.27	0.51	<0.1	<0.1
	II	0.01	0.06	0.00	0.18	0.18		
CEC me/100 g soil		11.5	16.8	8.8	22.3	28.5	24.5	30.2
ESP		45.8	54.6	23.2	66.1	49.4	0.1	0.2
Organic matter content, %		1.25	0.79	—	2.22	1.53	4.1	3.1
Bulk density, g/cm³	I	1.36	1.33	1.32	1.27	1.27	1.29	1.16
	II	0.98	1.09	1.28	1.05	0.92		
Particle-size distribution:								
Loss in HCl-treatment		10.73	15.52	28.33	2.10	2.34	7.38	3.06
1.00—0.25 mm		12.00	9.61	12.31	1.44	0.55	4.04	0.07
0.25—0.05 mm		52.36	39.58	42.93	4.08	3.43	10.68	8.11
0.05—0.01 mm		13.80	12.65	9.29	37.74	32.30	46.16	26.67
0.01—0.005 mm		2.62	3.14	2.30	9.29	9.02	5.40	9.60
0.005—0.001 mm		4.52	5.57	3.38	11.54	11.71	2.83	14.23
$<$ 0.001 mm		3.97	13.89	1.46	33.81	40.65	23.51	38.26

I = At the beginning, and II = at the end of the experiment
For soil types see p. 78 and p. 83

high suction gradient — is extremely slow through the thin but rather dry "film-like" moisture depletion zone, formed around the plant roots. As a consequence of this there is a peculiar micro-distribution pattern of soil moisture and the water supply of plants (especially of crops with a widely-spaced, scarce root-system) is extremely low. This phenomenon is clearly illustrated by the results of an evaporation column model experiment [19] As can be seen from the moisture-profile redistribution curves (Fig. 10), the drying was practically uniform within the whole column in the case of water and diluted NaCl solutions, but in the Na_2CO_3-treated (sodium saturated) variants the evaporated water could not be replenished from the relatively moist deeper layers in spite of the high suction gradient, because of the very low transport coefficients. Under such ecological conditions it is very important to establish a permanent vegetation with a dense root system, because it permits the rational use of the limited moisture resources of the soils [5, 27].

Unsaturated flow in salt affected soils

The most important practical applications of the unsaturated flow theory are:

- infiltration studies;
- determination of possibilities for the water supply of plants from the groundwater;
- description and prediction of salt accumulation processes from the groundwater.

Table 2

The influence of various Na solutions on the water retention of soils (Data of pF curves; moisture content in volume percentage)

Soil Code No.	Treatment	pF 0	0.4	1.0	1.5	2.0	2.3	2.7	3.4	4.2	6.2	ESP
349	H_2O	54.8	52.8	51.0	48.6	43.6	36.8	33.5	25.0	17.7	4.6	0.2
	$NaCl$											
350	0.05 N	54.8	53.3	51.3	49.4	43.8	39.6	33.6	26.3	18.1	4.6	4.2
351	0.1 N	51.1	53.6	51.6	50.1	44.5	40.1	35.3	27.6	19.1	4.6	5.9
352	0.5 N	57.4	55.7	53.2	51.3	47.7	44.3	39.3	30.3	20.6	4.6	28.4
	Na_2CO_3											
353	0.05 N	57.5	55.2	53.5	51.2	46.3	42.0	36.6	28.8	20.0	4.6	8.4
354	0.1 N	57.5	56.3	53.9	52.6	48.1	44.2	39.3	30.5	21.7	4.6	31.6
355	0.5 N	59.4	57.3	55.1	54.1	53.5	52.4	49.9	39.8	28.6	4.6	65.3
169	H_2O	51.6	49.9	48.5	47.7	45.2	41.5	33.2	21.6	12.5	2.7	0.1
	$NaCl$											
170	0.05 N	51.4	50.1	48.9	47.9	45.2	41.7	33.4	21.9	12.6	2.7	3.8
171	0.1 N	52.0	51.2	48.9	47.9	45.3	41.8	34.0	21.9	13.0	2.7	5.1
172	0.5 N	53.6	51.4	49.5	48.3	45.6	41.2	34.1	22.2	14.1	2.7	26.8
	Na_2CO_3											
173	0.05 N	53.0	51.3	51.1	49.5	47.1	43.6	36.4	24.2	14.1	2.6	8.6
174	0.1 N	53.4	51.8	51.5	50.7	47.8	45.7	38.6	26.7	17.2	2.8	32.1
175	0.5 N	55.6	54.4	53.6	52.5	51.0	49.5	46.1	32.2	20.6	3.1	61.1

For the description and prediction of salt accumulation processes from the groundwater (due to natural factors or human actions, secondary salinization and/or alkalization) a method was elaborated by VÁRALLYAY with the application of the unsaturated flow theory [15, 21, 27].

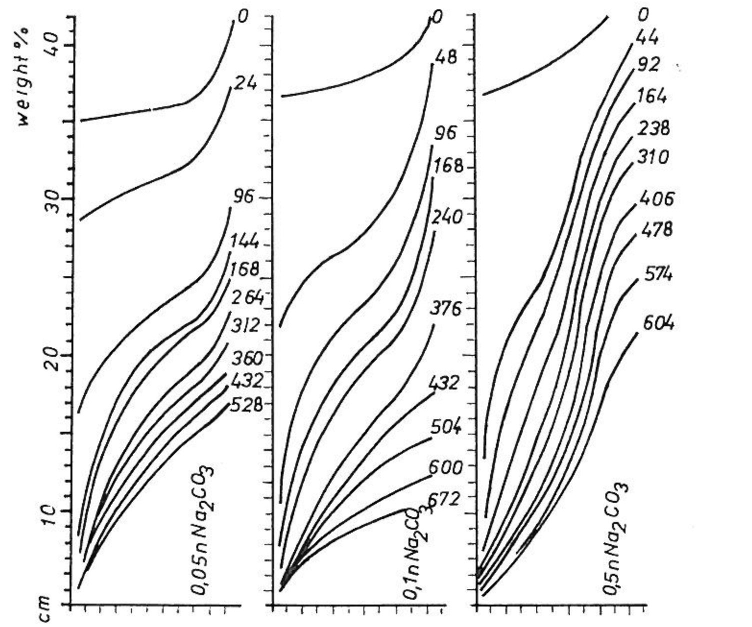
The hydrophysical approach includes four main steps:

1. Determination of unsaturated hydraulic conductivity as a function of suction ($k - \psi$ or $k - \theta$ relationship).

2. Based on the measured (or calculated or estimated) $k - \psi$ relationship, with the application of the simplified general unsaturated flow equation, a special type of set of curves can be constructed, indicating the direction of vertical capillary flow and the velocity of upward flow ($\bar{V} =$ cm/day) as a function of the suction profile ($\psi =$ water column cm) and the height above the water table ($z =$ cm).

3. For layered soil profiles the maximum upward capillary flow velocities (as a function of suction) at a given height above the water table can be determined only by an integrated analysis of the $k = f(\psi)$ relationship or by using the characteristic set of curves for the consecutive layers.

4. Between the soil surface and the rising or fluctuating water table an infinite number of variously stratified soil profiles may theoretically be distinguished. The above mentioned computations can be made for these stratified soil profiles and in this way the quantity of water which can enter the soil profile from the groundwater can be estimated in the case of a rising or fluctuating water table.



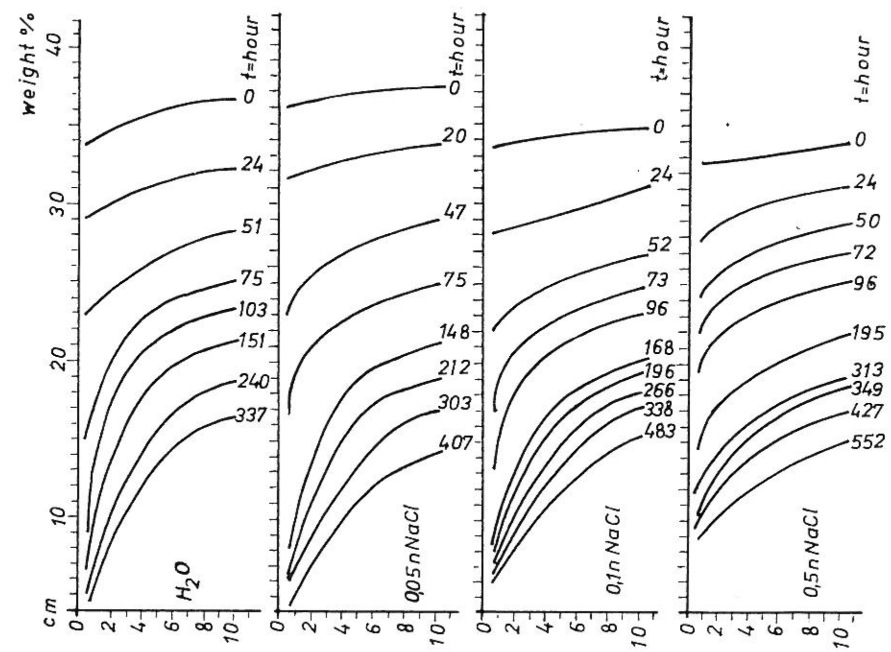


Fig. 10
Moisture profile redistribution in evaporation columns treated with NaCl and Na_2CO_3 solutions of various concentrations. Vertical axis: depth in cm. Horizontal axis: moisture content in weight percentage

By using the above summarized step by step approach, on the basis of directly measured or computed data for the time and territorial distribution of the suction (or moisture) profiles of soils, the direction and velocity of vertical capillary flow in the unsaturated soil layers between the soil surface and the water table can be determined and interpreted for soil profiles, mapping units or territories. By using forecasted values instead of measured

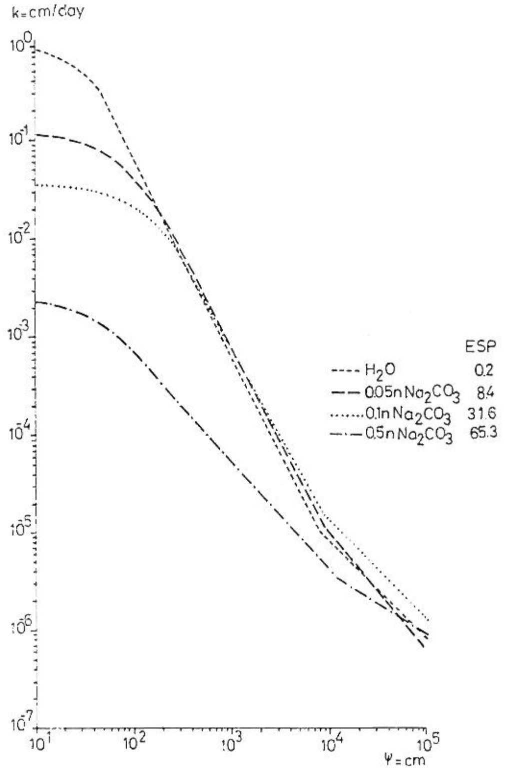


Fig. 11

Relation between capillary conductivity (k = cm/day) and suction (ψ = cm) in a clay loam (No. 349) under the influence of Na_2CO_3 solutions with various concentrations

ones (from meteorological and hydrogeological prognosis or from irrigation plans) a more or less accurate prognosis can be given for the water movement in layered, unsaturated soil profiles with a fluctuating water table, and the quantity of water entering the soil profile from the groundwater can be forecasted as well.

As a first approximation — disregarding the chemical and physico-chemical aspects (differences between the flow of water and solutions; interactions between the solid and liquid phases of the soils, etc.) — salt transport in the soil profile and salt accumulation in the soil from the groundwater can be described and/or forecasted on the basis of water flow (discussed above) and the measured, calculated or predicted concentration and chemical composition of the filtrating solution. The validity of this approximation is limited only to ideal cases. In natural soil—water—salts systems the differences between the water and solution flow (due to the reversible and irreversible, direct and indirect influences of the concentration and ion composition of the filtrating solution, and the interactions between the solid and liquid phases of the soils) have to be taken into consideration for the quantitative characterization of salt transport.

Only a few data are available in the literature on the influence of salinity—alkalinity on unsaturated flow. Illustrating the importance of the chemical composition of the liquid phase of the soil in flow studies, the results of a laboratory model experiment are shown in Fig. 11 [19, 27]. The flow of water and 0.05N—0.1N—0.5N NaCl and Na_2CO_3 solutions were studied in a clay loam topsoil. In the studied concentration range the influence of NaCl proved to be insignificant. ESP and moisture retention increased (Table 2), while hydraulic conductivity decreased, especially in saturated conditions (Fig. 7) and in the low suction range. The rate of k-decrease with increasing suction was moderated with increasing Na_2CO_3-concentration ("n" decreased). This is an indirect proof of non-Darcian flow behaviour in heavy-textured soils with high ESP. Unsaturated conductivity, calculated for the water-filled cross section of the soil matrix, increased with an increasing gradient of the acting forces: $\approx$ grad ψ: Fig. 11. As a consequence of this, the influence of Na_2CO_3 solutions ($\rightarrow$ high alkalinity, ESP) gradually decreased with increasing suction: it was only moderate in the medium suction range (pF 2.7—4.0) and in the high suction range (at pF 4.5—5.0) the k-values proved to be similar in all the variants ($\approx 1-3\times10^{-6}$ cm/day). But here, of course, the liquid flow has negligible significance. In these soils infiltration and downward flow (wet conditions,

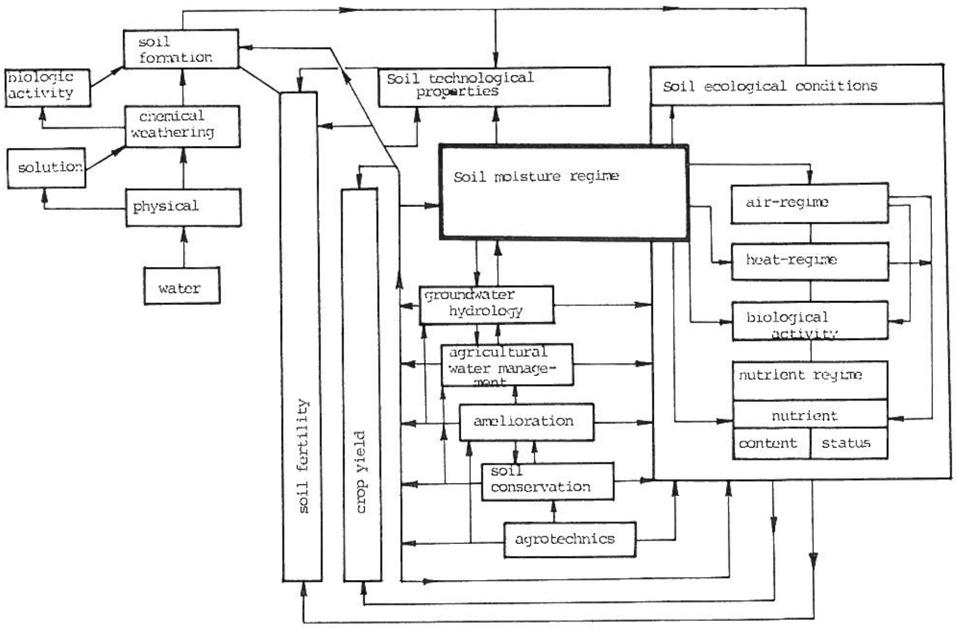


Fig. 12

The influence of soil moisture regime on soil fertility and possibilities of its regulation low gradient) are more limited than the upward capillary flow (dry conditions, high gradient) promoting progressive salinization and alkalization in the presence of a shallow, saline (Na_2CO_3) groundwater These unfavourable changes cannot be balanced by the traditional leaching and drainage techniques.

Relationships between salinity—alkalinity and low fertility due to extreme soil moisture regimes in Hungary

As has been reported by numerous authors [1, 2, 5, 6, 11, 29] most of the soil fertility limitations are directly or indirectly related to the moisture regime of the soils, both on a global scale (drought, mineral stress, shallow depth, water excess) [25, 32] and in Hungary (extremely light or heavy texture, salinity—alkalinity, salinity—alkalinity in the deeper layers, water-logging, solid rock near to the surface) [11]. Because the moisture content determines the ratio between the solid, liquid and gaseous phases in the soil, and influences the air and heat regimes of the soil, the biological activity, the space and time distribution of plant nutrients and their transformation and availability: the soil moisture regime regulates both the water and nutrient supplies of the plants. In addition, the soil properties influence the possibilities of the various uses of modern, mechanized, large-scale agrotechniques. These relationships are summarized in Fig. 12 [25].

For the demonstration of the close relationships between salinity—alkalinity and the extreme moisture regime (and, consequently, low fertility) four schematic maps are presented (indicating only the salt affected areas):

1. Limiting factors of soil fertility in Hungary (Fig. 13) [11]
2. Categories of Hungarian soils according to their hydrophysical properties (Fig. 14) [34]
3. Water regime types of Hungarian soils (Fig. 15) [30]
4. Main types of substance regimes in Hungarian soils (Fig. 16)

The complete maps were published in our previous papers [11, 30, 33, 34].

1. Limiting factors of soil fertility in Hungary (original scale 1 : 500 000) [11]:
   (1) Extremely light texture.
   (2) Strong acidity.
   (3) Salinity-alkalinity.
   (4) Salinity-alkalinity in the deeper layers
   (5) Extremely heavy texture.
   (6) Water-logging.
   (7) Severe water erosion.
   (8) Solid rock near to the surface (shallow depth).
2. Categories of Hungarian soils according to their hydrophysical properties (original scale 1 : 100 000) [34]:
   (1) Soil with very high infiltration rate (IR), permeability (P) and hydraulic conductivity (HC); low field capacity (FC); very poor water retention (WR).
   (2) Soils with high IR, P and HC; medium FC and poor WR.
   (3) Soils with good IR, P and HC; good FC; favourable WR.
   (4) Soils with moderate IR, P and HC; high FC, moderately high WR.
   (5) Soils with moderate IR, poor P and HC; high FC; high WR.
   (6) Soils with unfavourable hydrophysical properties: low IR, very low P and HC; high WR.
   (7) Soils with extremely unfavourable hydrophysical properties: very low IR, extremely low P and HC; low available moisture range (AMR).
   (8) Soils with good IR, P and HC; very high FC.
   (9) Soils with extreme moisture regime due to shallow depth.

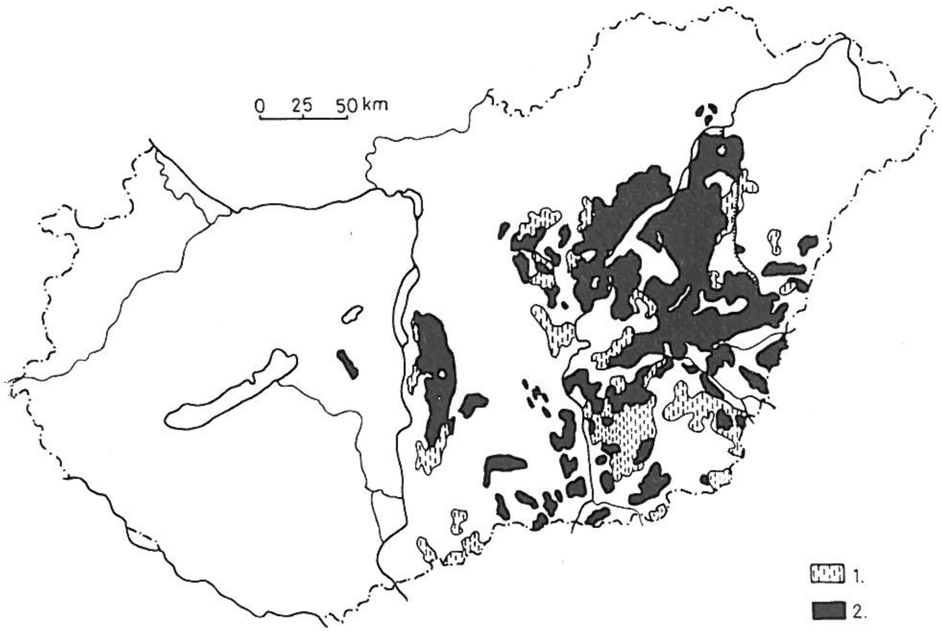


Fig. 13
Limiting factors of soil fertility in Hungary (original scale 1 : 500 000).
1. Salinity-alkalinity in deeper layers. 2. Salinity-alkalinity

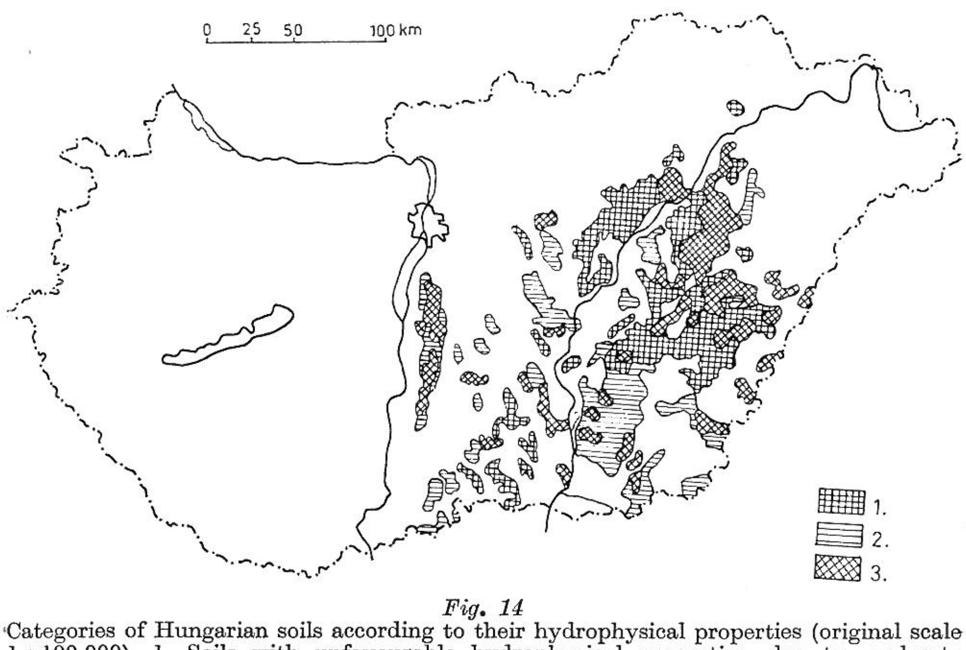


Fig. 14
Categories of Hungarian soils according to their hydrophysical properties (original scale 1 : 100 000). 1. Soils with unfavourable hydrophysical properties, due to moderate salinity and/or alkalinity. 2. Soils with unfavourable hydrophysical properties due to salinity and/or alkalinity in deeper layers. 3. Soils with extremely unfavourable hydrophysical properties, due to severe salinity and/or alkalinity

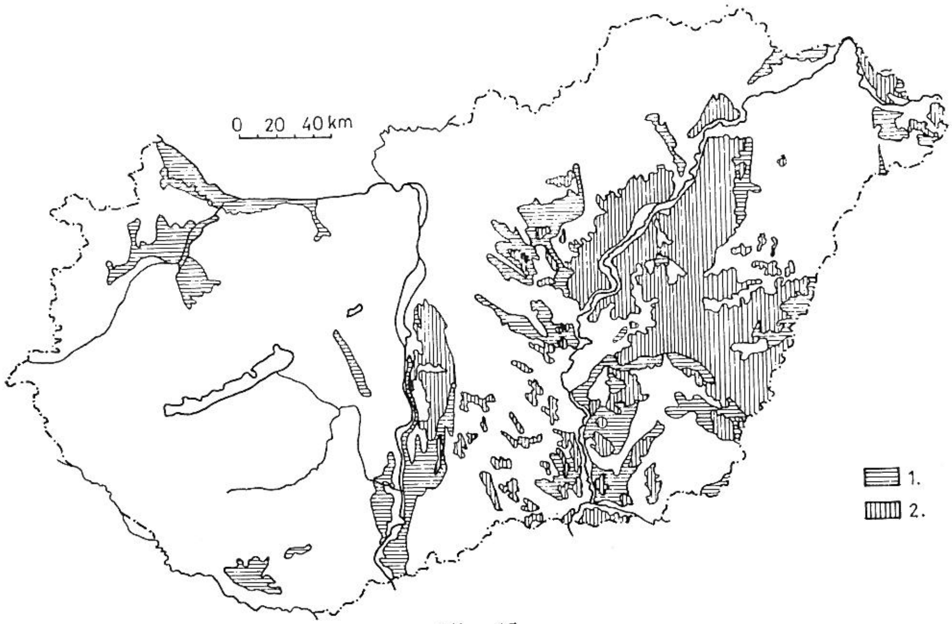


Fig. 15
Water regime types of Hungarian soils (original scale 1 : 500 000). 1. Groundwater-wetted type (upward flow is dominant). 2. Extreme moisture regime due to unfavourable hydrophysical soil properties

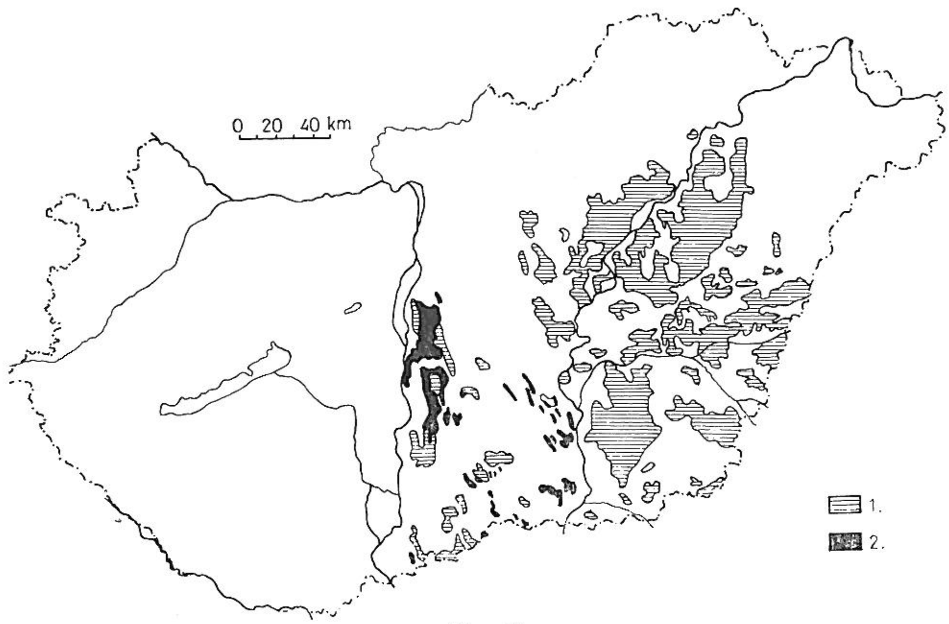


Fig. 16
Main types of substance regime in Hungarian soils (original scale 1 : 500 000). 1. Moderate accumulation of water soluble salts. 2. Strong accumulation of water soluble salts

3. Water regime types of Hungarian soils (original scale 1 : 500 000) [30]:
   (1) Heavy surface runoff.
   (2) Heavy downward flow.
   (3) Moderate downward flow.
   (4) Equilibrium-type.
   (5) Rapid filtration-type (light textured soils).
   (6) Groundwater-wetted type (upward flow is dominant).
   (7) Extreme moisture regime due to unfavourable hydrophysical soil properties.
   (8) Extreme moisture regime due to shallow depth.
   (9) Soils under the influence of rivers and surface streams.
   (10) Regularly water-logged areas.
   (11) Forests with special moisture regime.
4. Main types of substance regime in Hungarian soils (original scale 1 : 500 000) [30]:
   (1) Severe surface erosion.
   (2) Heavy leaching.
   (3) Moderate leaching.
   (4) Substance regime under the influence of temporary stagnant water within the soil profile, due to high atmospheric precipitation (pseudogley)
   (5) Organic matter accumulation in the surface horizons (as a consequence of extreme moisture regime due to shallow depth) (rendzinas).
   (6) Equilibrium-type.
   (7) Substance regime under permanent groundwater influence.
   (8) Heavy carbonate accumulation.
   (9) Moderate accumulation of water soluble salts and/or exchangeable Na^+.
   (10) Heavy accumulation of water soluble salts and/or exchangeable Na^+.
   (11) Organic matter accumulation (peats).
   (12) Negligible substance regime (sand).
   (13) Substance regime under the influence of rivers and surface streams.

The maps presented in this paper clearly prove the close territorial correlations between salinity-alkalinity, and salinity-alkalinity in the deeper horizons (Fig. 13.); the unfavourable hydrophysical properties of soils (Fig. 14.); the extreme moisture regime (Fig. 15.); and the "accumulation"-type substance regime (Fig. 16.).

All the maps were prepared on the basis of the map entitled "Soil factors of the agro-ecological potential of Hungary" (1: 100 000) [32], indicating the following factors (with a computerized 8-number code-system):

1 and 2: Soil types and subtypes (31 units);
3: Parent material (9 categories);
4: Soil reaction and carbonate status (5 categories);
5: Soil texture (7 categories);
6: Soil-water regime properties (9 categories);
7: Organic matter resource (6 categories);
8: Depth of the soil (5 categories).

On the basis of the 1 : 100,000 and 1 : 500,000 scale maps and their territorial data, conclusions can be drawn on the frequency, probability and potential factors of both extremes of the moisture regime (water-logging, too wet conditions — drought sensitivity), and their physiological and agronomical consequences (inadequate water supply of plants, problems posed by mechanized agrotechnical measures, etc.). Based on this information the necessity and the possibilities of theoretical, as well as realistic, rational and economical soil moisture regulation can be determined, the probable efficiency of the various measures can be forecasted, and proper technologies can be elaborated for the optimum variants. Consequently, the maps and the territorial data represent an adequate soil information basis for the establishment of an optimum (or nearly optimum) agricultural water management and for the elaboration, planning and execution of proper and rational measures for its realization.

The complete information material will be put into the Hungarian soil data bank, a computerized soil information system which is being organized by a team headed by the author and is now in the final stages of compilation.

Based on the experimental results and the computer-stored maps, conclusions can be drawn on the

— theoretical
realistic
rational and
economic

possibilities of an up-to date moisture (and substance) regime control of salt affected soils;

— preconditions for the efficiency of these human interventions, hydro- and agrotechnical measures (chemical, mechanical and biological operations aimed at the creation of an appropriate vertical drainage of the soil profile; surface and sub-surface drainage; optimum cropping pattern, etc.);

— necessity, possibilities and probable efficiency of the various measures designed to prevent the further development of salinization and alkalization processes.

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Discussion

YADAV, J. S. P.

(1) How is the moisture transmission characteristic affected by higher ESP value in the soil dominated by neutral salts instead of by carbonates of sodium?
(2) How is the availability of nutrients in general and of particular elements affected by the imbalance of moisture regime caused due to higher ESP values?
(3) Is the crack formation in the heavy textured soils promoting excessive infiltration rate mainly responsible for the rise in water table, or are there other soil characters and processes also, which lead to the rise in water table in these soils, as these soils are very prone to the development of water-logging on prolonged irrigation.
(4) What irrigation method and moisture regime (alternate wetting and drying or contin-

uous wet regime) through water management do you recommend for minimising rise in water table in heavy textured soils?

VÁRALLYAY, G.

(1) As regards the influence of various sodium salts on the saturated conductivity, two factors have to be taken into consideration:
1. The total salt content,
2. The ESP (according to the equilibrium between the solid phase and the concentration and ion composition of the filtrating solution).

Under the effect of the high electrolyte concentration of the soil solution a reversible flocculation of the primary particles takes place due to their low electrokinetic (zeta) potential. The floccule formed in this way is "stable" only in a certain concentration range and if the concentration decreases below the "threshold limit", the particles, which are not cemented or bound together, will be dispersed again. Consequently, the hydraulic conductivity (K) of highly saline soils is relatively high. When the electrolyte concentration of the permeating soil solution falls below the "threshold" concentration, the flocculating effect of high salinity becomes negligible and the physical consequences of high Na-saturation manifest themselves more strongly. Here, an intensive swelling takes place due to the high hydration of absorbed Na^+-ions and expanding clay minerals.

(2) The nutrient regime (content, availability, dynamics, etc.) of salt affected soils is strongly influenced by their extreme moisture conditions, due partly to high ESP-values. Under too dry conditions, the solubility of various plant nutrients is limited simply by their relatively high concentration in the soil moisture. Under too wet conditions, poor aeration prevents the oxidation (and consequently the availability) of plant nutrients, and the biological processes also retard the mobilization of the nutrient elements.

(3) There are at least two reasons of the rise of the groundwater table under salt affected soils:
1. Filtration from the soil surface
2. Horizontal filtration to the given area.

As a considerable part of salt affected soils are situated in the deepest part of the microrelief, surface runoff from the neighbouring regions can be considerable (sometimes results in water-logging) and the quantity of water calculated to a unit area can be much higher than the average or even actual precipitation. In heavy-textured, cracking alkali soils a significant part of this water can reach the water table through the cracks. Because in these low-lying areas the horizontal outflow is limited by the relief, this water surplus results in the rise of the water table. In several cases the horizontal inflow (seepage from water reservoirs, lakes, rivers, unlined canals, etc.) contributes to a considerable extent to the rise of the groundwater table either directly, or indirectly: by increasing hydraulic gradient (e.g.: in the recharge areas around the Hungarian Plain within the Carpathian Basin).

(4) In the Hungarian Plain irrigation methods of economical water use (sprinkling, drip-irrigation) are most rational due to the following reasons:
- Hungary is situated in the zone of supplementary irrigation, and only some special crops require high doses of irrigation water regularly;
- The availability of good quality water is limited (limited water resources, increasing water demand of industry, urbanization and recreation, water pollution by industry and agriculture).

At the same time these methods minimize the filtration losses and, consequently, the rise of the water table. In the Tisza I. Irrigation System more than half of the irrigation was done by surface methods (basin-irrigation, strip-board irrigation, furrow-irrigation, etc.). The uneven water distribution (as a consequence of imprecise land levelling in the case of these methods) besides the seepage from the unlined canals were the main reasons for the considerable rise in the water table, and the secondary salinization, alkalization and water-logging processes on about 120,000 hectares. In the Tisza II. and further irrigation systems, the irrigation methods of economical water use will be wide-spread with less hazard of rise of the water table and the development of undesirable soil processes. In spite of this, to prevent any harmful rise of the groundwater table, the application of proper drainage techniques would be necessary (at least locally).

SINGH, N. T.

In your presentation you mentioned that in solonetzic soils K vs. hydraulic gradient curve shows non-Darcian behaviour. Isn't it better to say that in such soils there is a threshold hydraulic gradient to start any flow?

VÁRALLYAY, G.
According to our measurements, in heavy-textured salt affected soils (high clay content, high amount of expanding clay minerals, high ESP) the saturated conductivity increases with increasing hydraulic gradient. This is a typical example of non-Darcian flow behaviour which was described by numerous authors. In the case of a porous material like soil, theoretically it is rather difficult to say that the flow is equal to zero. The minimum values, which we measured during our experiments (in the heavy-textured B-horizon of a Hortobágy alkali soil) were $K = 10^{-3}$—10^{-4} cm/day. With increasing hydraulic gradient more and more parts of the bound and capillary water become mobile, thus the K-value increases. At low suction range, most part of the water can be neglected from the viewpoint of flow phenomena: and this immobile state water shows "semi-solid" character.
GIRDHAR. I. K.
One of the figures of this lecture indicates that hydraulic conductivity curve with Na_2CO_3, NaCl and distilled water crossed each other at a particular suction value i.e. between 10^2 and 10^3 suction. This indicates that hydraulic conductivity is the same under the above treatments. Please explain why?
VÁRALLYAY, G.
In the literature only few data are available on the influence of salinity—alkalinity on the unsaturated flow. We carried out laboratory model investigations in this respect and our data prove that the influence of alkaline sodium solutions on the hydraulic conductivity is profound in saturated conditions and in the low suction range, and becomes moderate and negligible in the medium and high suction range, respectively.
The rate of k-decrease with increasing suction was moderated by increasing Na_2CO_3 concentration within the whole suction range: the slope of k-curves becomes slighter. Consequently, the influence of Na_2CO_3 solutions gradually decreased and in the high suction range (at pF 4.5—5.0) the k-values proved to be similar in all of the variants (1—3×10^{-6} cm/day). But here the liquid flow — of course — has negligible significance. This fact is an indirect proof of non-Darcian flow behaviour in this heavy-textured alkali soil. At the same time it means that in heavy-textured alkali soils the infiltration and downward flow (wet conditions, low gradient) are more limited than the upward capillary flow (dry conditions, high gradient). The latter becomes dominant and may result in progressive salinization processes in the presence of a shallow, saline groundwater and these processes cannot be balanced by the traditional leaching and drainage techniques.
SZABOLCS, I.
No question, rather an amendment to Dr. Várallyay's answer. Tisza I. System in Hungary was established in the nineteen fifties and Tisza II., the new system was completed about 25 years later. During its planning, all the experiences, good or bad, gained from Tisza I. were taken into consideration. A preliminary soil survey was conducted to predict the possible hazard of secondary salinization and alkalization, and the areas to be irrigated were selected accordingly.