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DRAINAGE DEPTH EFFECTS ON THE SALINIZATION OF SOIL

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Up to now, the impact of the horizontal drainage depth on the formation of the salt regime of soils in the aeration zone under irrigation, has not been solved yet, despite considerable research and experience gained recently in this field.

It is the present world practice to build the drainage network on irrigated lands at a depth from 0.75 to 3.5 m. It should be pointed out though that as far as drainage dimensions are concerned, views often differ within the same country(⁸).

Horizontal drainage is relatively a new development for most irrigated lands in the world, though drainage structures have been known since ancient civilizations.

If Soviet and foreign historians (B.V. Andrianov, G. Child, H. Fukuda and others) relate the beginning of irrigation with the VII-VIth millennia B.C., drainage structures are much "younger". It is evidently due to the fact that naturally drained lands were primarily put under irrigation. Besides, irrigated areas were relatively small. Soviet scientists N.I. Vavilov and B. V. Andrianov believe that the most ancient form of irrigation in mountainous regions was the so-called ravine-rill irrigation, followed later by basin irrigation. The latter permitted the creation of leaching regimes under the conditions of natural drainage.

Later, when irrigation gained in importance in poorly drained areas, literature suggested the first information either on drainage, or on occurrence of salinity. Thus, during his voyage to Egypt Herodotus described the drainage network in the Nile valley. Drainage canals were mentioned in connection with building basin irrigation systems in Egypt during the period of the first dynasty. This practice implied the creation in the floodplain of basins protected by levees along the river. Drainage canals were built to collect water from basins. By the beginning of the new era, there appeared in Egypt the so-called "summer" deepened. canals from which water was lifted by shadoufs (water-lifting wheels). This meant that draining and irrigating actions were combined similarly to those observed in medieval Khoresm. Strabom describes ditches and canals in Mesopotamia which diverted water from the Euphrates floodplain after floods (the IV-III millennia B.C.). Willcocks et al. believe that drainage canals were built there at the same time as irrigation canals.

B.V. Andrianov states that drainage canals appeared in China a millennium B.C. suggesting the data on a revealed system of drainage canals 40-70 cm wide, 120 cm deep, up to 60 m long. The glossary of the Merv oasis irrigation terms, compiled by a prominent mathematician Mohammed Al Khoresmi (the VIIth century A.D.), contains the term "mufriga", i.e., a canal for diverting excessive water. This suggests the existence of drainage canals at that time.

In the Fergana valley, one of the most ancient irrigation regions in our country, there has long been known the drainage system comprising open drains and canals called "zaurs". Those were as deep as 2 m, spaced at 70 m.

The second birth of drainage on irrigated lands was encouraged by the experience gained in drainage of humid lands. As is known, drainage of humid lands is aimed at diverting excessive water and maintaining groundwater tables under optimum moisture and aeration conditions. That is why the drainage network is to be provided at a depth from 0.5 to 1.2 m.

Rich experience gained in drainage of overwetted lands influenced the choice of drainage parameters for irrigated lands as well.

Thus, in Russia the first experimental drainage plots, established on irrigated lands in the Golodnaya Steppe, were similar—in their designs—to drainage systems. To study into salinization processes, in 1912 surface and subsurface drainage was provided on a badly saline plot of the experimental field in the vicinity of the K-3 canal. Drainage was laid as deep as 40-120 cm, spacing equalling 20 and 40 m. Leaching was applied on the lands provided with that drainage. The research resulted in as follows: the thickness of the leached soil layer depends mainly on drain depths; shallow drainage does not produce considerable decrease in ground water salinity; only constant leachings and the leaching regime of irrigation under proper field management, with the use of shallow drainage, can ensure good crop yields.

In 1914 the Solonchak Soils Section of the Station established a Velikoalekseevsky experimental drainage plot where the workers of the Golodnaya Steppe Station conducted experiments on soil desalinization.

In 1914 a high crop yield was obtained on this plot, while in 1915 all crops failed. The ground-water table was 1.1 m from the ground surface, the content of salts within a 1 m layer was over 380 t/ha. Provision was made for building drainage 1.2-1.5 m deep, drain spacing being 40 and 80 m. In 1916 the plot was leached and sown with cotton. Drain spacing equalling 80 m, the crop yield made up 4-7 q(*)/ha; drain spacing equalling 40 m, the crop yield made up 8-14 q/ha. In 1977 a series of repeated leachings was applied on this plot, the cotton yield was as high as 17.5 q/ha.

The results of the studies have shown that drainage being up to 1 m deep, the effect was temporary and it was necessary to repeat leachings. Leaching discharges of 15,000 m^3/ha could be considered satisfactory if being combined with drainage 1 m deep, drains being spaced at 50-60 m.

In 1922 subsurface drainage—1.2 m deep, drain spacing being 30 m—was built at the Station under the supervision of V.S. Malygin. But those parameters failed to produce the desired effect. Further experiments proved urgent necessity in deepening subsurface drainage up to 2-3 m. Proceeding from these results, in 1927-1928 the plot of deep horizontal drainage was established in the Zolotaya Orda region. This was the country's first plot of deep drainage. Drainage was made of tile tubes 20-25 cm in diameter, protected with a gravel layer, drains were spaced at 100-265 m and placed at a depth of 2.8-3.5 m.

The studies undertaken on the Zolotaya Orda drainage plot permitted V.S. Malygin and N.V. Makridin to give—for the first time—optimal drain spaces, accounting for the drainage depth and hydraulic conductivity under the conditions of Central Asia, as well as to determine leaching rates.

The most popular was the drainage plot of the Muganskaya Experimental Reclamation Station in Azerbaijan. In 1930-1931 provision was made for installing an experimental drainage network on an area of 600 ha. That network comprised six subsurface drains, one open drain and a subsurface collector. Drains were made of concrete tubes 200 mm in diameter, protected with three layers of crushed stone 10-15 cm thick. Drainage depth varied from 2.5 to 4.0 m.

(*) 1 quintal (q) equals 100 kg

Since that time Soviet irrigation practice is guided by the necessity of building mainly deep horizontal drainage on irrigated lands though views differ on this problem for the recommended range of depths varies from 2 to 4 m.

Drainage parameters corresponding to the optimal ground-water depth under irrigation are closely connected with the parameters dictated by the reclamation theory in our country which is based on the concept of the ground-water critical depth.

This concept was first suggested by B.B. Polynov (22) as early as 1930, who understood it as "such a space between the ground-water table and the soil surface, the decrease of which is responsible for the beginning of soil surface salinization." It should be pointed out though that this determination is erroneous for it does not regard other sources of salts migration in the soil, for instance, irrigation water, precipitation, infiltration leaching flows, etc., as well as the presence of other sources of salinization in addition to ground water.

According to V.A. Kovda (1946) by the critical depth of ground water with salinity exceeding 2-3 g/1 is implied one at which capillary water does not provoke salts accumulation in the soil root zone with the given irrigation regime and certain climatic, hydrogeological conditions (16). V.A. Kovda emphasized the fact that the above value was strongly influenced by ground-water salinity, soil texture, natural zoning of meteorological factors.

Similar opinion was stated by V.V. Yegorov et al (12) and N.G. Minashina (20). As indicated in (12), the ground-water depth at which ground-water evaporation from the soil stops under arid climate, is as follows: 3.5–4.0 m—for loess and silt loam; 3.0 m—for medium loam; 2.0 m—for fine loam; 1.2–1.5 m—for fine clay; 0.5–2.0 m—for sand.

I.N. Antipov-Karatayev (1) classifies the ground-water critical depth into: the absolute depth at which the boundary of the capillary fringe reaches the soil surface, and the relative depth at which secondary salinization begins to manifest itself.

Processing the numerous data of field studies undertaken on different experimental plots permitted the determination of the relationship between the ground-water critical depth and the maximum one—for the given conditions—as the function of ground-water salinity (Figure 1):

$$\frac{h_{kpc}}{h_{pc\,max}} = \frac{1.3\,(C_{if}-1)}{C_{if}+0.622} \qquad (1)$$

where, h_{kpc}—critical depth of ground water with salinity C_{2f};

$h_{kp\,max}$—critical depth, maximum for the given hydrogeological and climatic conditions and soil water properties.

There are other determinations of the critical depth concept, somewhat differing from the above. Thus, P.A. Letunov (^{18}), who studied thoroughly the laws of salt transfer by capillary flows in the Aral-Caspian lowland, determines the critical depth as one at which the velocity of capillary supply to the soil surface will be less than the rate of evaporation and transpiration from the soil surface. P.A. Letunov proves that the intensity of capillary input and transfer of salts depends only on the capillary properties of soils, their configuration and ground-water salinity.

Of interest is the determination suggested by D.M. Kats (^{13}). According to D.M. Kats by the critical ground-water depth is implied one at which salt accumulation within one annual cycle does not reach the limits dangerous for plants. Thus, according to D.M. Kats, the critical depth is no longer constant. It depends on the water regime of soils, including precipitation, type of treatments, etc.

The concept of the ground-water critical depth is closely connected by some researchers with ground-water critical salinity. Thus, O.A. Grabovskaya believes that critical salinity is the degree of ground-water salinity at which the seasonal water salinity totals 0 at the given ground-water depth. Figure 1 shows that absolute critical ground-water salinity is within 0–1 g/l; relative salinity at which the intensity of salts accumulation and the possibility of ground-water critical depth reduce by one half, complies

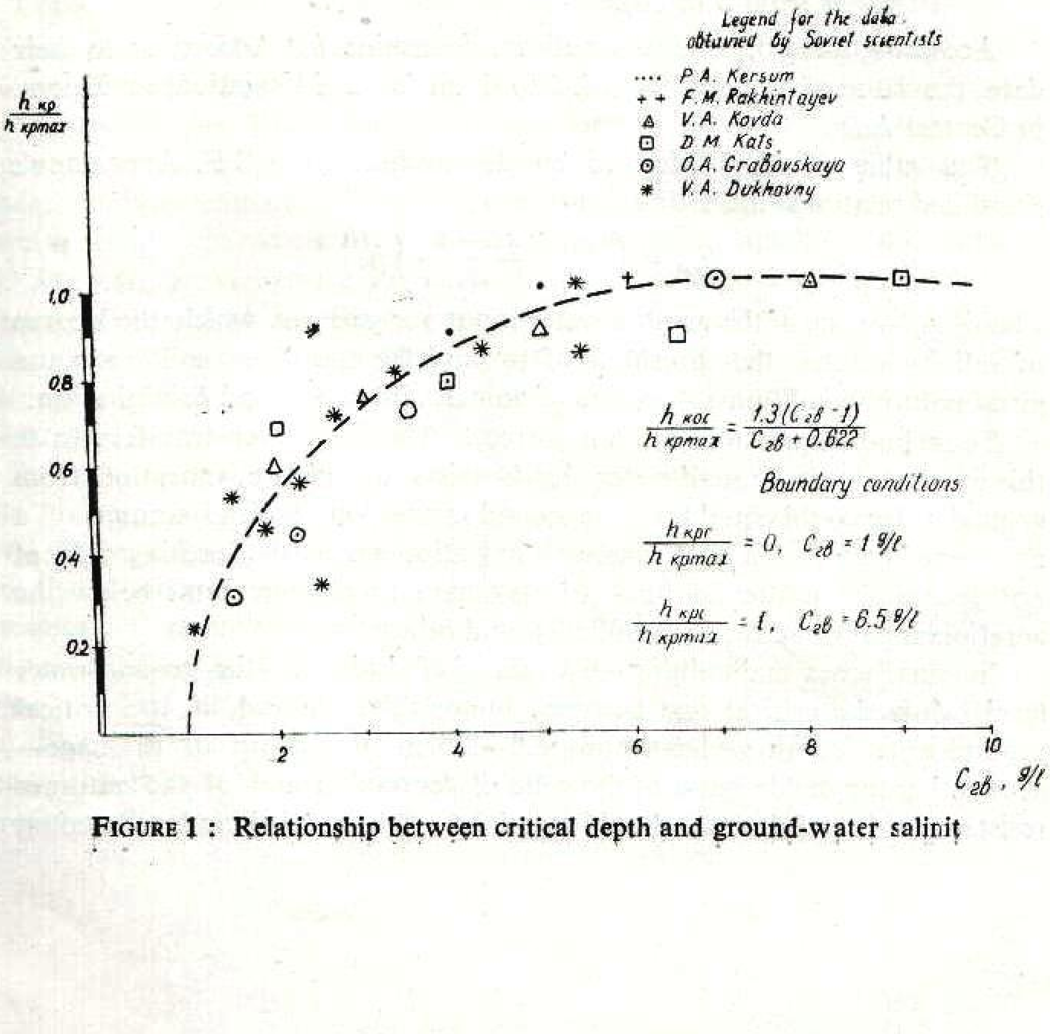

FIGURE 1 : Relationship between critical depth and ground-water salinit

with the parameters determined by V.A. Kovda, i.e., 1–2 g/l by dry residue.

Stemming from the recent concepts of physico-chemical hydrodynamics of porous media and existing mathematical models of salts transfer, A.A. Kavokin, E.A. Sokolenko et al (14) recommend to make use of the two concepts of the critical depth:

- critical depth of evaporation, h_o, at which ground-water evaporation equals practically 0;
- critical depth of salinity, h_{kp}, i.e., the minimal possible depth at which maximum concentration of salts in the soil under the given natural conditions does not exceed the threshold of salts toxicity for the given crop.

The value of these constants is determined as follows: The relationship between the value of unit evaporation (q) and potential evapo-transpiration (q_o) is derived by the power relationship:

$$q_z = q_o \, e^{\frac{-z^n}{\alpha}} \tag{2}$$

where, Z—ground-water depth;

n—power from 1 to 3;

α—depends on soil physical properties and the type of crop (α varies from 5 to 30).

Accepting $q_z = 0.01\ q_o$, the authors determine h_o. According to their data, the value of h_o varies from 2-5 to 6 km for the irrigation conditions in Central Asia.

The value of h_{kp} is derived by the authors from S.F. Averyanov's simplified relationship:

$$h_{kp} = \left(1 - \frac{q_{kp} - \epsilon}{q_o} \right) h_o \tag{3}$$

where, q_{kp}—value of the ground water input per year, at which the degree of salinity reaches the threshold of toxicity for the given soil, crop and given natural conditions; ϵ—value of annual infiltration and precipitation.

These both expressions are not correct. The first never transfers to 0, this means that no ground-water depth exists at which evaporation from ground water could equal 0. The second expression takes no account of a number of factors: entry of salts with irrigation water; the leaching role of not the entire infiltration but of its share which percolates below the aeration zone (or active zone of soils), and others.

In most cases maintaining—by means of drainage—the ground-water level below the critical one becomes impossible. Indeed, if the critical ground-water depth varies within 2.0—3.5 m, the depth of drainage—accounting for the decrease of the cone of depression and of the entrance resistance value of drains—should equal 3.5—5.5 m. Taking into account the modern machinery, the maximum possible depth of horizontal drainage —even if a "trough" is provided—makes up 3.5 m, the greater depth can be achieved only with the use of vertical drainage. Designing and construction of drainage as it is being practised in the Soviet Union, show no quest for lowering the ground water table below the critical one. The efforts are aimed at minimizing water exchange and salt exchange between the aeration zone and ground water, limiting the maximum drainage depth to 2.5–3.5 m.

As it was justly emphasized by V.A. Kovda(15), the formation of views of foreign scientists regarding the drainage depth was influenced—to a considerable extent—by the transition from drainage of overwetted lands to drainage of irrigated lands. V.A. Kovda points out that the relatively shallow drainage of depth (1.0-1.5 m) has found wide use in zones of insufficient humidity and not in arid areas where irrigation only supplements natural precipitation. Taking the UNESCO FAO review (Drainage of Salty Soils, Rome, 1973), V.A. Kovda suggests the data on drainage for different European countries:

	Depth of drainage, (m)	*Drain spacing, (m)*
Romania	1.5	20-50
Spain	0.9-1.2	10-60
France	1.2	12-80

According to V.A. Kovda, the success of shallow drainage is due to low aridity and rather high precipitation. Indeed, though the authors of the papers in the FAO review do not submit data on evaporation, precipitation values prove the correctness of V.A. Kovda's statements concerning poor climatic aridity in the above countries. Thus, in France these areas are characterized by annual precipitation equalling 600 mm (M. Alleman, I. Vigneron); in Spain in the Guadalquivir River valley—571.6 mm(11); and in the Ebro River valley—536 mm(I. L. Unger). But even under these conditions there is a tendency for constructing deeper drainage (1.8-2.0 m) to better regulate the ground-water table during operation.

In the work dealing with the experience on reclamation of salt-affected soils in Iraq, J.H. Baumans, W.C Hulsbos et al.(4) show changing the views on drainage of overwetted lands to drainage of irrigated lands. They state that drainage in the humid zone (J.N. Luthin, 1957; Visser, 1954) is necessary to remove excessive water and to maintain ground water under optima conditions of humidity and aeration; that is why drainage is to be provided at a depth of about 0.5—1.2 m. As for drainage in the arid zone, it is to provide the required water-air regime, but at the same time it is to protect the soil from danger of salinization caused by ascending flows in capillars.

As for the West, the basic principles of drainage to be applied on irrigated lands were first formulated in 1947 by the Drainage Manual Committee for the Imperial Valley and in 1954, by the U.S. Salinity Laboratory. Views differed. Thorne Peterson (1954) and Buringh (1960) focussed primary attention on controlling ground-water tables, ignoring amounts of drainage water. The range of ground-water tables varied from 1.2–1.5 m (according to J.E. Christiansen) to 3.0 m, according to Buringh (1960). The authors realize that soil salinization cannot be prevented by means of drainage only, exemplifying this by the Diajailah Valley soils, Iraq. These soils became saline due to insufficient intensity of leaching regimes, ground-water tables occurring at a depth of 2.0 m and more from the ground surface.

The comparison of two types of drainage with depths of 1.1 m and 2.0 m and drain spaces of 52 m and 28 m, hydraulic conductivity approximating 1 m/day, has shown that deeper drainage permitted the decrease in total water consumption and the volume of drainage water. The authors emphasize the fact that drainage systems operate more steadily throughout the year under such conditions. Given below are these theoretical data:

	Drainage depth	
	1.1 m	*2.0 m*
Total water application, m^3/ha	9,000	7,400
Drainage flow, m^3/ha	4,950	4,550
Mean daily discharge, m^3/ha		
the 1st period—30 days	19.3	13.4
the 2nd period—135 days	30.6	16.5
the 3rd—5th periods—195 days	1.2	10.0

During the period from December 9, 1956, to December 31, 1957, total water application within the Diajailah area made up 18,310 m^3/ha, the drainage flow equalling 4,630 m^3/ha. Drainage was actually built at a depth of 1.1 m, drains were spaced at 25 m, hydraulic conductivity equalling 0.8 m/day. Thus, admitting the advisability of the drainage depth equalling 2.0 m, the authors, however, cannot compare it with a greater drainage depth. It should be emphasized that total water application, net, is actually 2.5 times greater than the design rate.

Similar data were obtained in Central Asia. In Khoresm and Tashauz, for example, where drainage is as deep as 2.0–2.2 m, total water application, net, should be brought up to 17–18 thousand m^3/ha to maintain the normal salt regime, thus decreasing seasonal salt accumulation. In Iraq and in the USSR (Khoresm) such results were obtained under the conditions of high aridity: evaporation equalling 1,200–1,400 mm, precipitation, 100–220 mm per year.

It should be noted that improper evaluation of these data results in the obvious erroneous views. Thus, A. Arar(²) suggests that Buringh and V.A. Kovda, attaching great importance to salinization—provoked by capillary ascending flows—forget about the decrease in the desalinizing effect of irrigation on ground water. In A. Arar's opinion, construction of a drainage system and implementation of leaching procedures, especially with regard for water losses from canals and adjacent areas, will be responsible for the decrease of ground-water salinity: the closer to the ground surface is ground water, the more rapid will be the process.

As an example A. Arar suggests the same Daijailah area in south-western Iraq where ground-water table occurs at a depth of 75-110 cm, Satisfactory desalinization was obtained after leaching the 1.5 m soil layer, the initial ground-water salinity equalling 20 mmho/cm. They managed to maintain soil solution salinity within 2.0-3.5 mmho/cm in the 0-60 cm soil layer. The author points out though that when these lands were not treated during the two summer and one autumn months, soil solution salinity increased, reaching 6.6-7.7 mmho/cm per one season.

A. Arar suggests the data obtained in Syria. When growing cotton on heavy soils, ground-water table occurring at a depth of 80-100 cm from the ground surface, ground water use makes up 43-50 per cent of total water consumption, while it equals 28-35 per cent on light soils. In case ground-water table is as deep as 120 cm, ground-water use makes up 29 and 13 per cent respectively. The share of total water consumption becomes negligible with shallower ground-water depths.

A. Arar tries to prove that there is no necessity in building deep drainage since ground water becomes gradually fresh. The closer to the ground surface is ground water, the more rapid is the freshening effect. This permits not to be afraid of salinization in future and at the same time to improve reliability of water supply for plants.

A. Arar takes no account of the fact that the reclamation regime suggested by him is unstable and unreliable, and is fraught with danger of salinity restoration. This is proved by the author's data. Water amounts meant for leaching exceed considerably those saved due to sub-irrigation. As noted above, when assessing Bauman's data, A. Arar mentioned the area where theoretical water requirement was estimated at 9,000 m³/ha, though actually more than 17,000 m³/ha of water were used, which is two times greater than evapotranspiration.

M. Elgalaly's opinion concerning the relative depth of drainage is similar to that of Soviet scientists. M. Elgalaly believes that soil salinity can be prevented if ground-water table is close to the critical one and lands are irrigated with adequate rates.(⁹)

Drainage is to receive sufficient amounts of water in the early stages of reclamation and is to be deep enough to prevent salinization in the next stages.

In the initial stage of reclamation, in the presence of stable soils, open drainage can be built for it is characterized by greater water-intake capacity, compared to subsurface drainage. In other cases drains should be built of the two types: when meant for the leaching period they are to be 0.9–1.25 m deep, spaced at 10–100 m; while when meant for regulating the ground-water table drains are to be provided at a depth of 1.5-3.0 m and spaced at 300–1,000 m.

M. Elgalaly is absolutely correct believing that drainage depth depends on the value of ground-water evaporation, its salinity and change, hydraulic soil conductivity, type of crops grown, irrigation regime.

Both V. A. Kovda and M. Elgalaly believe that the ground-water table can be maintained at a depth of 70-90 cm to ensure maximum crop yields grown with ground-water salinity equalling 1.5-2.0 p.p. m.

The opinion of T. Talsma (Australia) is similar to the views of Soviet scientists. T. Talsma experimented with different soil types on the Murrumbidgee area.(24) The area is characterized by chloride salinity resulting from the effect of ground-water salinity. Stemming from Philip's and W. Gardner's theoretical concept of the model of settled diffusion and from the data of the field experiments, T. Talsma has derived a relationship between ground-water evaporation and ground-water table occurrence, $K = f(S)$, where, S is soil ability to water absorption depending on capillary conductivity, K (Figure 2).

T. Talsma states that ground-water table lowering results in the hyperbolic decrease of evaporation. To prevent salt accumulation the ground-water table should be limited to a depth at which evaporation does not exceed 0.1 cm/day(19).

G. Kovach believes that no salt accumulations occur in the soil layer in the presence of fresh irrigation water if the ground-water table is maintained within the levels of "0" water exchange, i.e., the value of infiltration to ground water equals the value of ground-water evaporation. G. Kovach suggests the appropriate curves.

The views of the U.S. reclamationists on the drainage depth differ. In the forties, i.e., during the first years of drainage construction, they laid drainage in the Imperial Valley at a depth of 1.8-2.0 m, drains spacings equalling 60-130 m; later on, in the Coachella Valley drainage was provided at a depth of 2.1-2.4 m. The recent tendency is to place drainage at a greater depth, up to 2.7-3.0 m.

The Manual for selecting the economical drainage depth worked out by the US Bureau of Reclamation in the late fifties, recommended that drainage be provided at a depth of 2.4-2.7 m. This was based on the technico-economic calculations supported by L. Dumm's and R.I Winger's formula, as well as by the data of different technologies and costs applied at that time. At present, stemming from the same relationships and new technological parameters of drainage construction costs, J. N. Christopher and R. I. Winger(⁶) optimized calculations which showed that the maximum depth of drainage made by using the trench method makes up 2.7–3.0 m, while that of drainage made with the application of the trenchless method is 2.4 m(²⁵).

In these calculations account is made of the drain spacing—drain depth relationship, as well as of the change in the construction cost per unit of area depending on the depth, ignoring maintenance costs, use of water for irrigation and the leaching effect. J. Van Schilfgaarde in his book "Drainage for Agriculture" (1974) neglects practically the impact of the ground-water table on the drainage depth (²⁵). The chapters written by P. A. Raats, W. Gardner and I. D. Roades are the exception.

The empirical values of the critical pressure head above ground water, existing in the US practice, are studied by P. A. Raats and W. Gardner (h_{cr} is the critical pressure head).

The critical pressure head is such an ordinate at which water conductivity factor, $K=f(\overline{W})$; where, $\overline{W}$ is moisture content—becomes equalling 0 (at $h=0$, $k=K$). Comparing the formulas determining this value, the authors indicate considerable difference in absolute and relative values of this concept. Nevertheless, the authors emphasize the importance of capillary ground-water input for salt accumulation, suggesting the appropriate method to calculate this value (taking no account of ground-water salinity and sorption processes).

Citing W. Gardner's early calculations (1960), the authors prove that in the experiments undertaken on the Pachappa loams—ground-water table occurring within 0–90 cm—the decrease of evaporation is insignificant, approximating 10 mm/day. At a depth of 90 cm, the decrease of evaporation retards noticeably, sharply stopping at a depth of 180-360 cm (Figure 3). Evaporation decreases quite insignificantly with further ground water lowering. As far sandy soils, similar change is observed at a depth of 150 cm. The authors suggest Shaw's and Smith's opinions based on their own experiments. It resides in the fact that on loams and clays as a whole, the ground-water table occurring at 3 m and greater depths is responsible for the decrease of maximum capillary rise and impossibility of reaching the ground surface by capillary water.

It should be pointed out though that the authors of this theoretical, highly sophisticated work do not suggest any conclusions stemming from their data, and recommendations on the depth of drainage installation. Only the section written by I.R. Roades, indicates quite rightly that compared to overwetted lands the minimal ground-water table should be maintained at much greater depths on irrigated lands. This is due to more intensive evaporation. The author recommends that ground-water table be at a depth of 180–200 cm on medium cohesive soils.

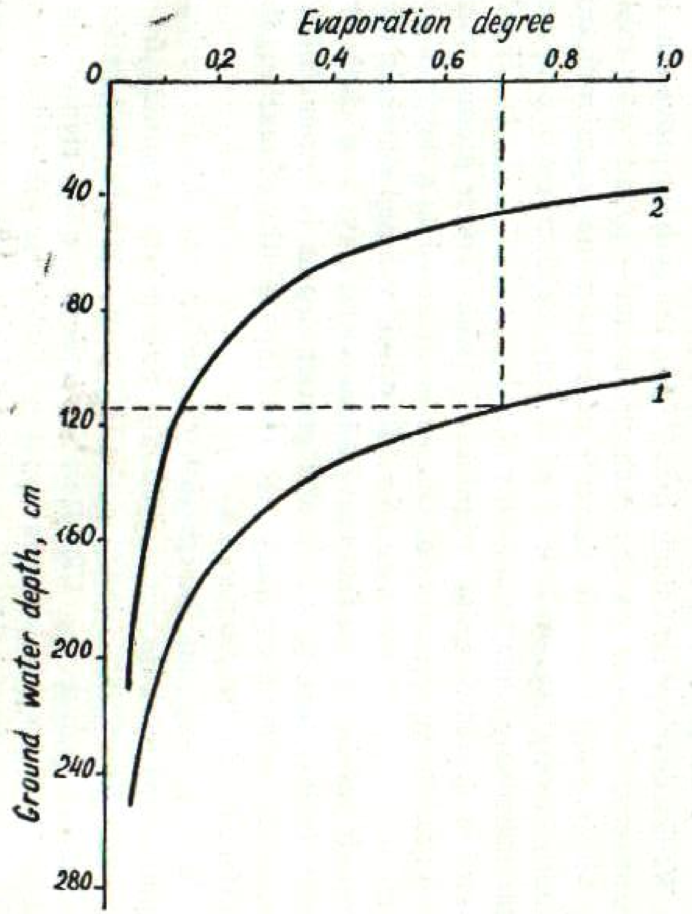

FIGURE 2 : Relationship between ground-water evaporation and ground-water depth for two soil types: 1-Yander loam; 2-Tipai clay.

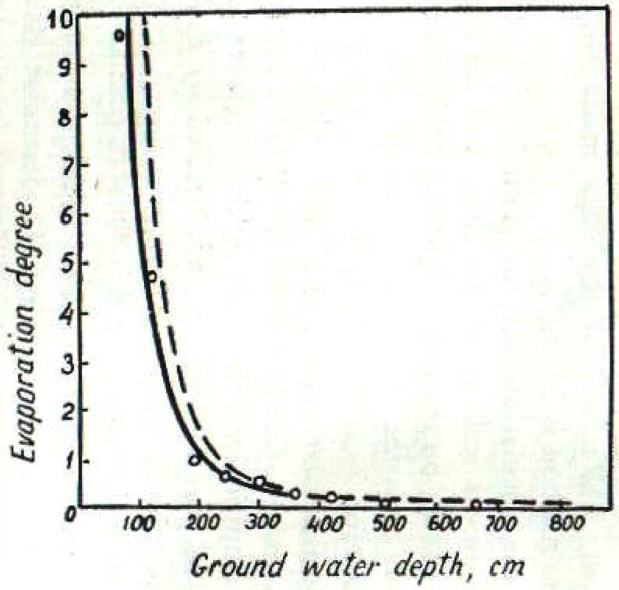

FIGURE 3 : Relationship between ground-water evaporation and ground-water depth, according to W. Gardner.

Of considerable interest is the work by J. Van Schilfgaarde(28) which is somewhat different from his previous works. J. Van Schilfgaarde agrees that compared to other statements, the critical depth method is more preferable. Stemming from the works by W. Gardner and P.A. Raats, J. Van Schilfgaarde derived an equation to determine the critical depth:

$$Z_{max} = -\alpha^{-1} \ln(1-K/q_{max}), \tag{4}$$

where, α—soil property describing the relative degree of change of water conductivity factor, resulting from head acting on ground water:

$$\alpha = \frac{1}{K}\, dk/dh;$$

K—hydraulic conductivity of saturated flow;

q_{max}—maximum input.

The author compares the results obtained with the values calculated, using other formulas, and states that as far as loams and clays are concerned, the critical depth is characterized by favourable similarity and is known to equal 175-180 cm. As regards other soils, especially sands, deviations are considerable: from 89 cm derived, from J. Van Schilfgaarde's formula to 659 cm received, using other formulas.

Realizing the complexity of interaction between root zone, soil moisture and suction force, J. Van Schilfgaarde tries to find the alternative of the "ground-water critical depth" concept as a criterion to control favourable conditions in the root zone, understanding it as a descending component, preventing intensively salt accumulation in the soil solution.

The calculations made, using the author's model, and cited to prove the above statement, seem to show that the 10 per cent excess of irrigation requirements as to evapotranspiration permits ensuring the absence of salt accumulation at the ground-water level $Z_{max} = 10\delta(\delta = 15$; $Z_{max} = 150$ cm), when only 20 per cent of evapotranspiration is taken from ground water. It is to be emphasized though that J. Van Schilfgaarde does not suggest the data on ground-water salinity intensity of ground-water capillary rise and therefore it is difficult to judge the validity of the calculations suggested by him.

Similar disadvantages are found in the work by P.A. Raats,(23) dealing with salt spreading in the root zone. It ignores the ground-water level and salinity, diffusion salt transfer; it averages—with time—the effect of transpiration, evaporation and leaching share; the drainage flow is taken as an abstract value depending neither on the ground-water table nor on its change; irrigation water only is taken as a source of profile salinization. But salt accumulation cannot be characterized only by the intensity of the descending component. That is why J. Van Schilfgaarde is correct, stating that the ground-water depth should be considered as one depending on the volume of water use and its regime.

In the opinion of Soviet reclamationists, there exists a direct relationship between drainage and irrigation network parameters—drainage depth, system's and field's efficiencies, ordinates of hydromodule and drainage modulus—and ground and irrigation water salinity, soil water properties, climatic factors.

Theoretical conclusions found in this sphere, coincide with the conclusions of soil scientists, resulting from a considerable volume of field observations. Thus, for each zone known to have its peculiar soil, climatic and hydrological features, N.G. Minashina(2) has set up a relationship between critical salinity and ground-water table, with due regard for the amounts of water used for total water consumption and drainage (Table 1). According to N.G. Minashina, water amounts lost by evaporation and transpiration involve ground-water use, while by critical drainage the value of the leaching discharge under blind basin conditions is meant; when moving on to real conditions, this value should be corrected by a value of natural ground water "inflow-outflow".

As was mentioned in(8) included in the first volume "State of Art in Irrigation", a concept of optimal land improvement regimes and their parameters has been devised in the USSR, the choice of which is verified with regard for natural and anthropogenic factors. In this case, the prevailing factor is salt concentration in ground water. Under most natural conditions a semi-automorphic regime is recommended for saline ground water. Under this regime there occurs minimal exchange between ground water and the aeration zone: the ground water input value approximates 10-15 per cent of evapotranspiration; the required leaching regime is achieved at 5-10 per cent excess of irrigation requirements as to moisture deficit, water consumption by plants being included. The required ground-water depth varies from 0.7 to 1.1 h_k where h_k is the height of capillary rise.

Ground-water salinity being lower than 2 g/l, a semi-hydromorphic regime is recommended, when nearly 50 per cent of total water consumption is met by ground-water supply. In this case the volume of water used for leaching is insignificant since the intensity of salt accumulation is modest when ground-water salinity is poor. As a whole, irrigation water supply does not exceed 60 per cent of total water consumption provided the semi-hydromorphic regime was applied properly. The appropriate ground-water depth meant to ensure optimal conditions of water supply within the root zone, makes up 0.5-0.7 h_k. Basically, these figures are in good agreement with the recommendations suggested earlier by V.A. Kovda.

It will be recalled that by the optimal land improvement regime is implied such a drainage-irrigation relationship at which the total of irrigation water meant both for wetting the root zone and maintaining the required salt regime of soils is minimal. We approach the presence of descending flows as the pledge of the favourable regime in the aeration zone

TABLE 1

RELATIONSHIP BETWEEN DRAINAGE FLOW VALUE, GROUND-WATER SALINITY AND GROUND-WATER TABLE [IRRIGATION WATER SALINITY EQUALLING 0.25 g/l]

Oasis	Ground-water depth, (m)	Critical salinity, (g/l)	Total water application 1000 m³/ha, at:	
			critical drainage	evaporation + transpiration
Sherabad	1.0	1.5	14.0	15.0
	1.5	3.2	6.2	9.4
	2.0	12.9	1.5	6.0
	2.5	25.4	1.5	5.5
Bukhara	1.0	1.7	12.4	13.8
	1.5	2.7	7.2	10.8
	2.0	9.3	2.0	7.1
	2.5	19.2	1.5	6.7
	3.0	22.8	1.5	7.0
Vakhsh	1.0	3.2	6.2	8.9
	1.5	6.8	2.7	7.9
	2.0	14.2	1.5	7.9
	2.5	19.1	1.5	7.9
	3.0	27.1	1.5	7.0
Khoresm	1.0	2.5	7.8	13.2
	1.5	3.2	6.2	11.6
	2.0	4.8	4.1	11.9
	2.5	6.5	2.8	11.5
Chardzhou	1.0	2.0	11.3	12.4
	2.0	5.9	3.7	7.5
	3.0	11.4	1.7	6.6

but only in case these flows exceed ascending ground-water flows. Poor intensity of ascending flows in the root zone is achieved when ground-water is deep. Thus, the tendency of descending flows prevailing under the conditions of minimal irrigation water use depends on the ground-water depth. It is precisely under-estimation of the importance of ground water salinity and sharply decreased intensity of input as the ground-water table lowers that led J. Van Schilfgaarde and his colleagues to erroneous conclusions.

The ground-water depth to be maintained within drain spacings during vegetation to ensure the favourable salt regime, can be determined by the salt balance of the aeration zone:

$$\pm\Delta S = O_p \,.\, \eta_{mn} \,.\, C_{op}+O_c \,.\, C_{oc}(1-a)-S_{yp}+(E_m+U)_i \,.\, C_{i\beta}- \\ -[O_p \,.\, (1-\eta_{mn}) \,.\, d_2+\beta O_p+O_c \,.\, a]\, C_u \qquad (5)$$

where, $\pm\Delta S$ — change of salt reserves in the aeration zone;
O_p — irrigation requirements, net, equalling the design water consumption aiming at meeting water needs during vegetation;
O_c — precipitation during vegetation;
S_{yp} — salt removal by the crops;
$(E_m+U)_i$ — evaporation and transpiration met by ground water during the irrigation interval;
η_{mn} — field irrigation efficiency (0.5–0.8);
d_2 — efficiency fraction used for infiltration, in parts of unit;
β — excess of the irrigation rate as to moisture deficit;
a — share of precipitation infiltrating below the ground-water level;
C_{op}, C_{oc}, $C_{i\beta}$, C_u — salinity of irrigation water, precipitation, ground water and of infiltration water, respectively.

C_u can be determined in the course of field observations or tentatively, using the formulas by Panin; V.R. Volobuyev and others, depending on the soil salinity degree.

Remembering that our task is to prevent salt accumulation, as well as accounting for that precipitation salinity, C_{oc}, and S_{yp}, approximate O, we obtain:

$$O_p \,.\, \eta_{mn} \,.\, C_{op}+(E_m+U)_i \,.\, C_{i\beta} = [O_p(1-\eta_{mn})d_2+O_p\beta+O_c\alpha]C_u \qquad (6)$$

Let us express the value of ground-water input to the aeration zone by means of S.F. Averyanov's formula:

$$(E_m+U)_i = U_o\left(1-\frac{h_i}{h_k}\right) \qquad (7)$$

where, U_o — total evaporation from the ground surface;
h_i — ground-water level;
h_k — height of the capillary ground-water rise adopted for each locality and crop as one for which intensity of the capillary rise makes up 0.02 of q_{max}.

Then solving formulas (6) and (7) relative to h_i. we obtain :

$$h_i = h_k\left[1-\frac{O_p(1-\eta_{mn})d_2+O_p\beta+O_c a]C_u-O_p \,.\, \eta_{mu} \,.\, C_{op}}{C_{if} \,.\, U_o}\right] \qquad (8)$$

With insignificant precipitation occurring during vegetation; for example, in arid zones, the formula is simplified:

$$h_l = h_k \left\{ 1 - \frac{O_p}{U_o} \cdot \frac{C_{il}[(1-\eta_{mn})d_2+\beta]-\eta_{mn} \cdot C_{op}}{C_{i\beta}} \right\} \qquad (9)$$

On the basis of this relationship, there have been determined the required mean ground-water levels during vegetation for different Central Asian areas. The observations show that providing the optimal land improvement regime ($O_p/U_o = 0.9$) depends on the values of C_{op}, C_{if}, β, η_{mn}, d_2 (Table 2). The critical depth has been determined, using the data of lysimetric observations for different irrigated areas in Central Asia, given in Figure 4(10). The data on field irrigation efficiency and its components are taken from N.T. Laktayev's work(17).

The above relationships indicate approximate results, since they comprise—as averaged—salt transfer mechanism and salinity; no account is taken of diffusion transfer; as suggested by S.F. Averyanov it is accepted that quantitative and qualitative impacts of evaporation and transpiration on the water-and-salt transfer are identical. Besides, no account is taken of the spatial character of work of drainage and irrigation within an irrigated plot, as well as of more intensive mobility of toxic salts.

Comprehensive field studies undertaken—under our supervision—by B.E. Milkis, V.G. Nassonov and E.I. Uzenbayev in state farms No. 1a and 10a in the Golodnaya Steppe, in the collective farm "Pravda" in the Khoresm District, have shown that taking into account all the above factors, the ground-water table within the intensively are artificially drained area can be higher than that determined by means of the approximate balance solution.

As an example, we are suggesting the data of the studies conducted in state farm No. 1a in the Golodnaya Steppe. An irrigated plot (Figure 5) 8 ha in area is intensively drained with the use of trenchless drainage 3.0 m deep (hydraulic conductivity equalling 0.4-0.6 m/day) and a collector 4.5 m deep. The plot has a series of observation and piezometer wells, a meteorological and radiation ground, a tensiometer pit to a depth of 3.0 m, and a water meter to observe water supply and out-flow of drainage water. All elements of the water and salt balance are recorded by means of the above technical observation facilities.

Within the period described, i.e., the vegetation period of 1977, water was applied twice, using heavy rates of 3,200-3,300 m^3/ha. During this vegetation period total evapotranspiration made up 628 mm; $\frac{O_p}{U_o} = 1.1$; $\beta = 0.2$; the average drainage modulus equalling 0.12 l/s ha. Figure 6 shows changes in ground-water tables, moisture content in the aeration zone, total evaporation, physical evaporation, transpiration, etc. Tables 3 and 4

TABLE 2

DETERMINATION OF REQUIRED GROUND-WATER LEVELS, AVERAGE DURING VEGETATION FOR CENTRAL ASIAN IRRIGATED REGIONS, ENSURING OPTIMAL LAND IMPROVEMENT REGIME

Region	Soil	h_k (m)	C_o (g/l)	C_r (g/l)	η_{mn}	d_2	C_u (g/l)	h_t		
								$\beta = 0.1$	$\beta = 0.2$	$\beta = 0.3$
Golodnaya Steppe (old zone)	loam	3.8	1.0	6-7	0.65	0.71	5.5	3.11	2.85	2.53
Golodnaya Steppe (new zone)	loam	3.8	1.0	8-10	0.72	0.75	8.0	3.13	2.82	2.52
Fergana Valley	loam	3.4	0.3	3-4	0.62	0.70	3.5	2.44	2.13	1·83
Kzylkum area	loam	3.3	1.2	6-7	0.60	0.80	5.5	2.80	2.31	2.07
Karshi Steppe	sandy loam	4.10	0.5	3-5	0.69	0.70	3.5	3.37	3.05	2.72
Bukhara	loam	4.40	0.7	6-8	0.60	0.75	6.0	3.23	2.95	2.60
Chardzhou	sandy loam	3.30	0.6	3-5	0.60	0.85	3.0	2.58	2.36	2.15
Khoresm	sandy loam	3.80	0.7	3-5	0.63	0.85	3.0	3.19	2.85	2.58
Khoresm	intercalation of sand and sandy loam	2.40	0.7	3-5	0.63	0.85	3.0	1.96	1.80	1.62

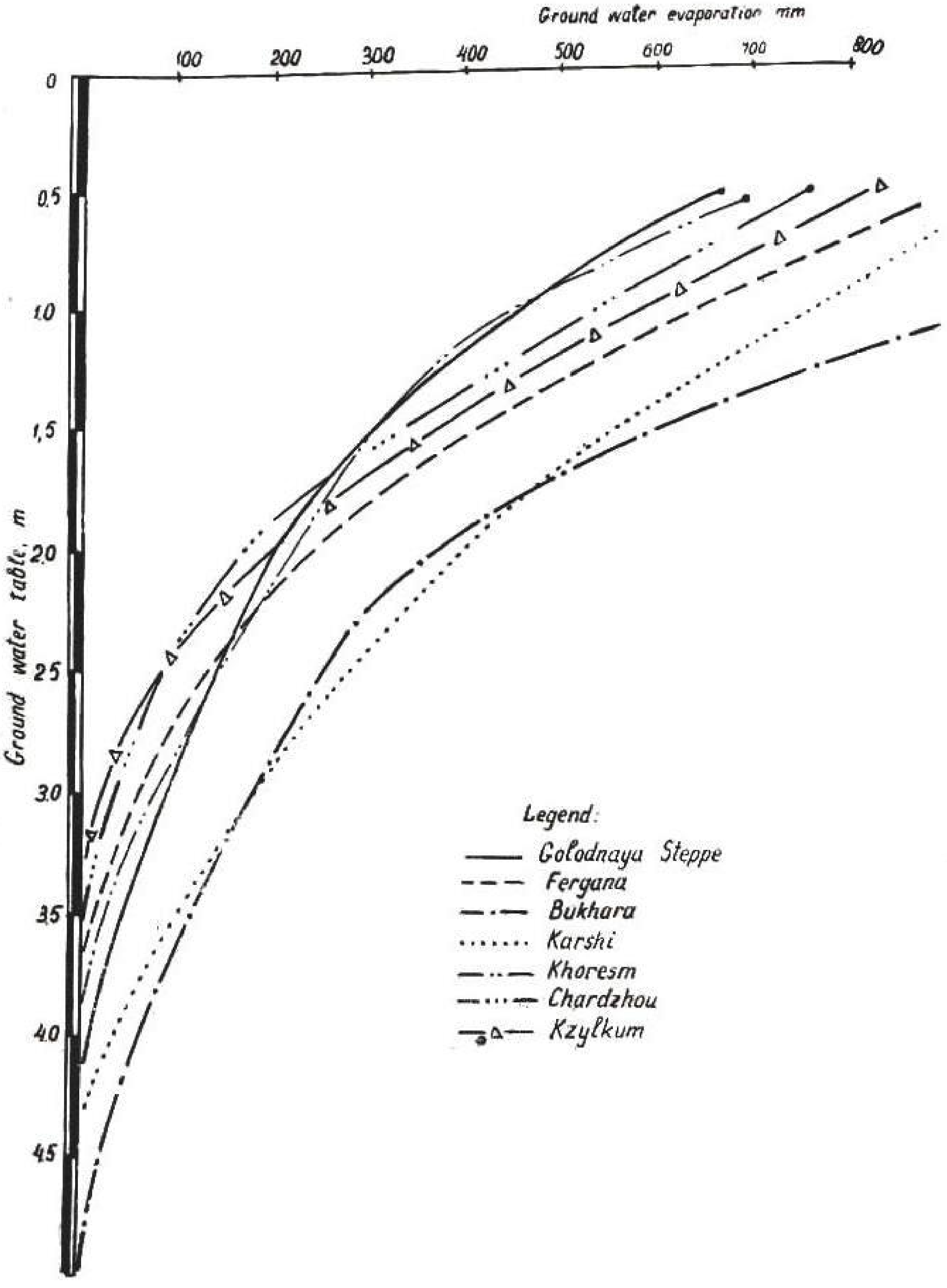

FIGURE 4 : Ground-water evaporation—ground-water depth curve for different Central Asian regions

suggest water and salt balances. As is evident from the observations made during the vegetation period, ground-water tables averaged 2.0 m, which was responsible for the unfavourable salt regime of the aeration zone with salinity of ground water equalling 12-15g/l and that of infiltrating water, 7-9 g/l. Indeed, as far as the observation period is concerned, the

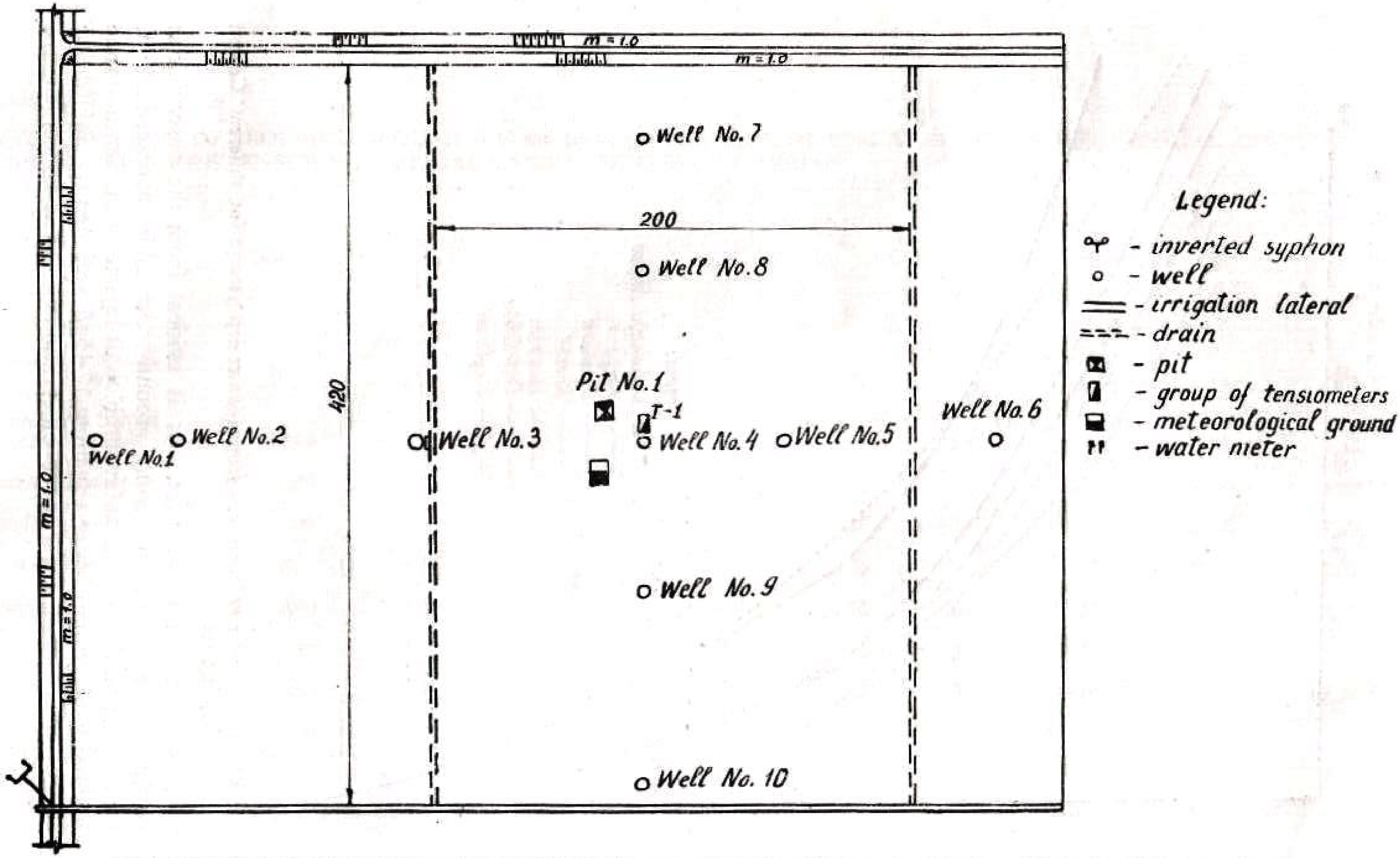

FIGURE 5 : Layout of the experimental plot, 21.2 ha in area, equipped with flumes, state farm No. 1, the Golodnaya Steppe

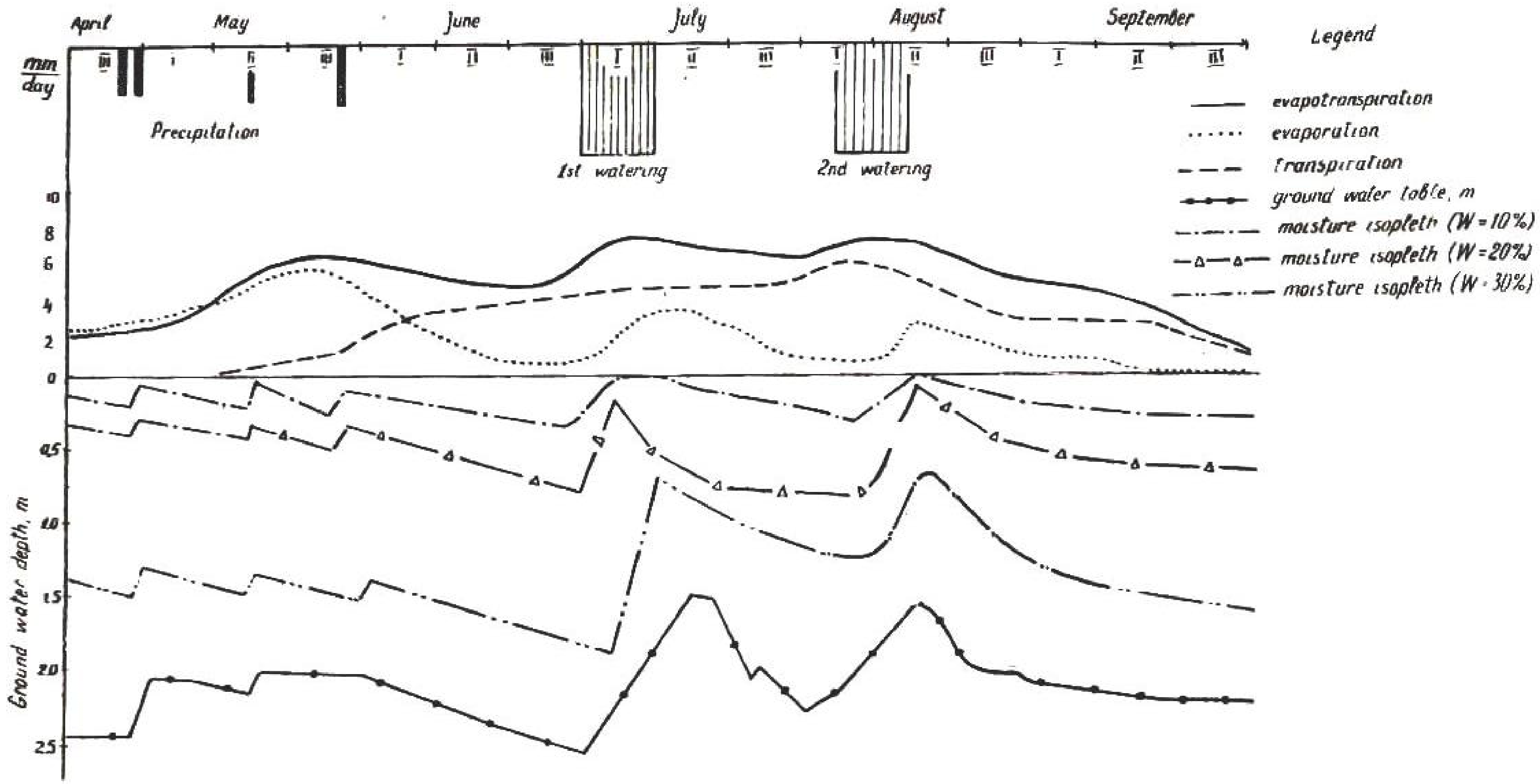

FIGURE 6 : Change in the content of major elements of the soils water regime in the aeration zone within the plot of state farm No. 1, the Golodnaya Steppe

salt balance of the aeration zone as a whole is in good agreement with the design data of balance equation (5) cited earlier, though differs widely both as to periods and migration of toxic salts, threatening plants, growth and development. Of special importance is migration of toxic salts known to have easily mobile Cl′, Na^+ ions. During the vegetation period the amount of Cl′, for example, with the profile of the aeration zone decreased, on the average, from 0.06 to 0.015 per cent in all profile horizons (Figure 7). Readily mobile and most toxic, but poorly absorbed ions, are easily removed from the profile under good drainage conditions and descending —even periodic—flows. The difference in the salt balance made up 20–30 t/ha.

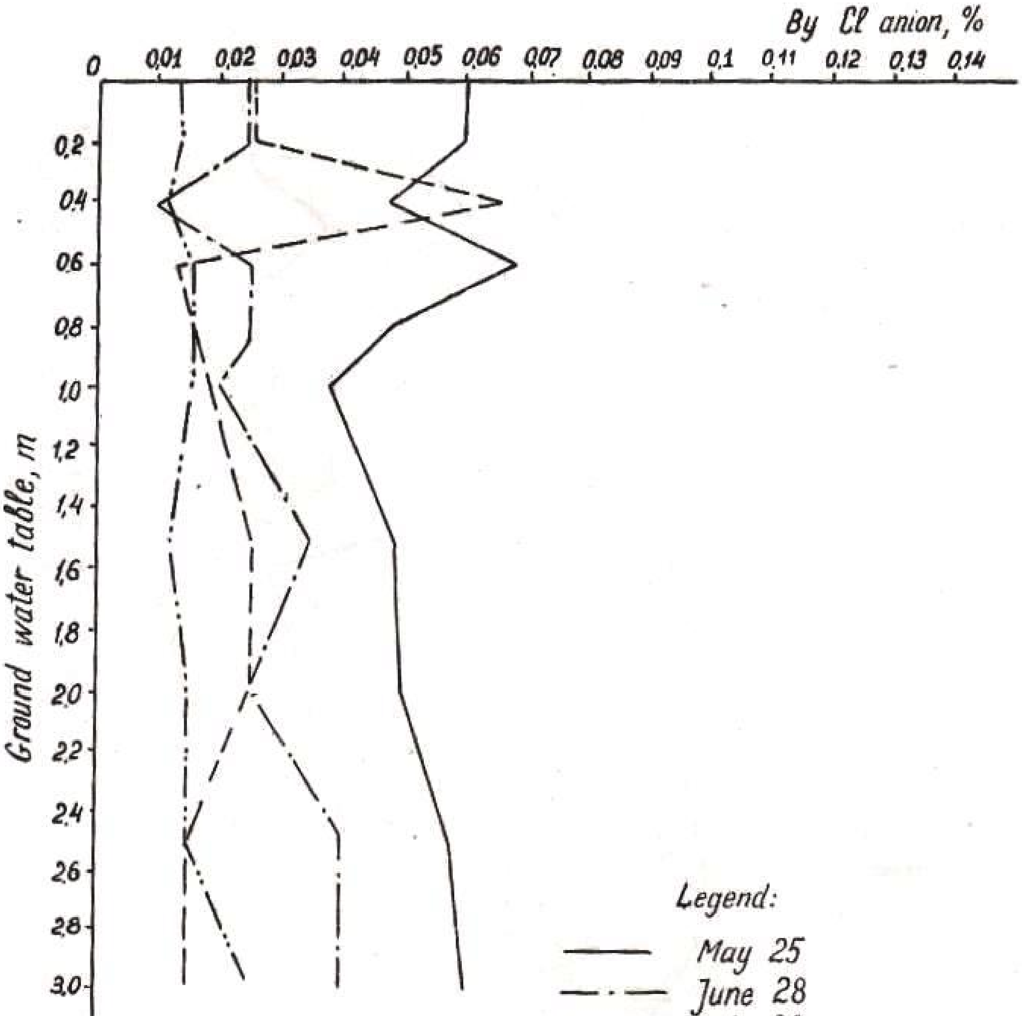

FIGURE 7 : Dynamics of soil salinization in the experimental plot of state farm No. 19, the Golodnaya Steppe

TABLE 3

WATER BALANCE OF THE AERATION ZONE BY PERIODS, STATE FARM NO. 1a, GOLODNAYA STEPPE

(in m³/ha)

Item of water balance	Periods				
	Before 1st watering June 10-July 1	1st watering July 1-July 6	Before 2nd watering July 7-Aug. 4	2nd watering Aug. 5-Aug. 14	After 2nd watering Aug. 15-Sept. 10
Change of water content in aeration zone	−948	+1646	−1409	+1567	−1147
Change of water content in ground water $\pm\mu\Delta h$	−240	+ 880	− 448	+ 540	− 480
Evaporation	+170	+ 192	+ 201	+ 330	+ 240
Transpiration	+740	+ 342	+1136	+ 450	+ 760
Total :	−278	+3060	− 520	+2887	− 627
Ground-water evaporation	+321	—	+ 448	—	+ 547
Precipitation	+130	—	—	—	+ 160
Irrigation	—	+3300	—	+3200	—
Infiltration to ground water and drainage	−101	− 273	+ 20	− 470	− 98
Total :	+351	+3027	+ 328	−2730	+ 609
Error of closure	72	33	− 192	+ 157	− 18
in per cent	+6.0	+1.0	−10.3	+50.3	−1.2

The major reason of this phenomenon is in the fact that salts accumulation from ground water in thé aeration zone profile occurs due to ground-water evaporation, while only some portion of salts is transferred to the soil as a result of transpiration. Ground-water supply is responsible for transferring only some portion of salts taken up by plants, while in the course of transpiration the other portion of salts is not transferred at all. This conclusion results from studying the generalizing monography by D. Bowling(5) and M.A. Beloussov's work(3). For example, D. Bowling suggests the data showing that maize takes up 245 mmoles of cations per

TABLE 4

SALT BALANCE DETERMINED BY DRY RESIDUE AND SUM OF TOXIC SALTS IN AERATION ZONE EXPERIMENTAL PLOT, STATE FARM NO. 1a, GOLODNAYA STEPPE

Items of water balance	Periods					Total
	Before 1st watering June 10-July 1	1st watering July 1-July 6	Before 2nd watering July 7-Aug. 4	2nd watering Aug. 5-Aug. 14	After 2nd watering Aug. 15-Sept. 10	
Design items						
Entry of salts with irrigation water		$\frac{+17.10^{*}}{+8.23}$		$\frac{+16.3}{+7.83}$		$\frac{+33.4}{+16.06}$
Ground-water evaporation	$\frac{+44.94}{+24.07}$		$\frac{+62.72}{+30.46}$		$\frac{+73.84}{+33.9}$	$\frac{+181.5}{+88.43}$
Infiltration to ground water	$\frac{-8.1}{-3.6}$	$\frac{-21.84}{-9.80}$	$\frac{-9.60}{-4.35}$	$\frac{-37.6}{-16.9}$	$\frac{-.84}{-.6}$	$\frac{-84.98}{-38.25}$

Total :	$\frac{+36.84}{+20.47}$	$\frac{-4.74}{-1.57}$		$\frac{+53.12}{+26.11}$	$\frac{-21.3}{-9.07}$		$\frac{+66.0}{+30.3}$	$\frac{+129.92}{+66.24}$
			$\frac{+48.38}{+24.54}$			$\frac{+44.7}{+21.2}$		
Actual availability of salts reserves	$\frac{513.75}{274.1}$		$\frac{641}{321}$		$\frac{487.5}{184.5}$	$\frac{675}{214}$		
Change in salts reserves	$\frac{+127.25}{+46.9}$	$\frac{-153.5}{-136.5}$				$\frac{+186.5}{+29.9}$		$\frac{+161.25}{-60.1}$
Error of closure, % to salt volume	$\frac{+13.9}{+7.4}$	$\frac{-36.9}{-64.5}$				$\frac{+27.32}{+4.25}$		$\frac{+4.6}{-59.0}$
Difference	$\frac{+80.41}{-26.43}$	$\frac{-201.88}{-161.10}$				$\frac{+14.8}{+8.3}$		$\frac{+31.33}{-126.34}$

(*) The numerator is dry residue ; the denominator is the sum of toxic salts.

100 g of dry residue which is equivalent to 8 per cent. If this is added by the balanced amount of anions, the content of salts will make up 16 per cent of dry residue.

Considering the fact that dry cotton—according to M.A. Beloussov—weighs 250-270 g at the end of vegetation, it can be found that a plant has up to 4-5 t/ha of salts during this period. D. Bowling indicates that absorption of salts and pushing them out or, in other words, "ion respiration" of roots, are responsible for constant transformation of some ions into cell material and pushing other ions out, these occurring at different rates. According to D. Bowling, active movement of ions in two directions is opposite to the increase of concentration. No explanation is found in the terms of physics and chemistry, remaining the biological process. That is, evidently, why during a season salts are taken up in the quantity 2-3 times greater than that available by the end of vegetation. A part of some salts does not rise in the course of transpiration. More thorough research is to be undertaken in this sphere to differentiate salts migration caused by plants and evaporation, enabling in future to find ways to decrease the drainage depth and use of irrigation water.

During the period of high physical evaporation—which lasts till July 15 in Central Asia, as far as cotton and alfalfa are concerned—we consider it necessary to ensure ground-water depth approximating the one recommended in formula (5), and then to partially backup ground water, thus intensifying ground-water transpiration. Such experiments were undertaken in the collective farm "Pravda", the Khoresm District. Those proved the conclusions concerning salts dynamics without backup and demonstrated the possibility of the ground-water table rise in the period of intensive transpiration.

The studies conducted on water-balance plots, have shown that resulting from the growing intensity of mobile ions migration, differentiation of plants' role in salt transpiration and, finally, spatial character of irrigation and drainage interaction, the ground-water depth recommended by formula (5) and Table II should be lowered by 15-20 per cent under sufficient drainage conditions, ensuring ground water lowering by 4 cm and more per day after water was applied.

To take account of the spatial character of dynamics of moisture and salts in soils, to determine the rates of infiltration and capillary input during an irrigation interval and, thus, to calculate the dynamics of salts in the aeration zone, there were designed models, using Richards' two-dimensional equation(27).

$$C(W)\frac{\partial H}{\partial t} = \frac{\partial}{\partial X}\left[K(\overline{W})\frac{\partial H}{\partial X}\right] + \frac{\partial}{SZ}\left[K(\overline{W})\frac{\partial H}{\partial Z}\right] + F(Z;t;W)$$

$$+Qg[h(O;t);\delta(x),\delta(Z\text{–}Zd)] \tag{10}$$

where, W — moisture content;
$C(W)$ — specific moisture content;
t — time;
$K(\overline{W})$ — hydraulic conductivity of soil;
H — head;
$F(Z, t, W)$ — intensity of evaporation and transpiration or of water application;
Qg — drainage flow to a drain to a depth of Zd, depending on head within the drain space, $h(O; t)$.

The relationship between hydraulic head and moisture content is derived as follows:

$$H = \varphi(W) - Z$$

where, Z — depth of soil layer;

$$C(W) = \frac{1}{d\varphi/dW};$$

$\varphi(W)$ — the relationship between capillary pressure, φ, and moisture content, determined using two A.I. Golovanov's formulas :

$$\varphi(\overline{W}) = h_k \left[\frac{1}{a} \ln \frac{m - W_o}{W - W_o} \right]^{1/\alpha} \; ; \; W > W_o \tag{11}$$

$$\varphi(W) = \frac{W - W_M}{W_k - W_M} (h_M - v\, h_k) - h_M ; \; W < W_o \tag{12}$$

where, W_o — minimum water capacity;
W_M — maximum hydroscropisity;
m — porosity;
v — conjugating coefficient;
a, α — constants.

Accounting for non-linearity of task (10), it is solved using the difference scheme by Neiman-Eddy(27). This solution permits the determination of head values and moisture contents at all points in the filtration area, ground-water dynamics, as well as the velocities field to forecast the salt regime.

Unlike the models used by J. Van Schilfgaarde and his followers, the model described involves both ground water and capillary input. That is why it permits the determination of the limits of ground-water level dynamics within the parameters as those determined by means of approximate calculations.

Using expressions (7), (9) and some others, an optimization model can be derived, based on the overall cost of irrigation and drainage with due regard for the water resources used.

It is necessary to find the minimum of the function of the overall cost per 1 ha of the irrigation system:

$$\overline{\Pi}_{ce} = \overline{\Pi}_{gp} + \overline{\Pi}_{op} \rightarrow \min \tag{13}$$

$$\overline{\Pi}_{gp} = n\overline{K}_{gp} + \text{Э}_{gp} \tag{14}$$

$$\overline{\Pi}_{op} = n\overline{K}_{op} + \text{Э}_{op} + \Phi_{fp}$$

$$\overline{K}_{pg} = \overline{C}_{gp}\,\frac{10000}{B} + C_k\,.\,\overline{l} \tag{15}$$

$$\overline{C}_{gp} = (H_{gp} - h_{mp})\,(aH_{gp} + b) + (gH_{mp} + q_{gp}\,.\,Q_{gp}) \tag{16}$$

$$\overline{C}_k = [(H_{gp} + 1.2) + m(H_{gp} + 1.2)^2]\,\overline{l}_{\Upsilon} \tag{17}$$

$$\text{Э}_{gp} = (a_M + m_M]\overline{K}_{gp}$$

$$\Pi_{gp} = \overline{C}_{gp}\,(n + a_m + m)\,\cdot\,\frac{10000}{B} + \overline{C}_k(n_1 + a_m + m_1) \tag{14a}$$

$$\overline{K}_{op} = \overline{C}_{op}\,.\,\overline{l}_{op}$$

$$\overline{K}_{op} = \overline{Q}_{op}\,.\,f(q_{op};\,\eta_c)\,.\,\overline{l}_{op}$$

$$\overline{\text{Э}}_{op} = (a_{op} + m_{op})\overline{K}_{op}$$

$$\Phi_{op} = q_{op}(n\overline{C}\,.\,\Phi_{op} + \overline{C}_{\text{э}kc})$$

$$\overline{\Pi}_{op} = \overline{Q}_{op}\,.\,f(q_{op};\,\eta_c)\,.\,l_{op}\,.\,(n + a_{op} + m_{op}) + q_{op}(\overline{C}\Phi_{op} + \overline{C}_{\text{э}kc}) \tag{15a}$$

where, $\overline{\Pi}_{oc}$ — overall cost of the irrigation system;

$\overline{\Pi}_{gp}$ — overall cost of the collecting and drainage network;

$\overline{\Pi}_{op}$ — overall cost of the irrigation net work;

$\overline{K}_{gp}$, $\overline{K}_{op}$ — specific capital investments per 1 ha of the drainage and irrigation networks, respectively;

$\overline{\text{Э}}_{gp}$, $\overline{\text{Э}}_{op}$ — specific operational costs per 1 ha of the drainage and irrigation networks, respectively;

$\overline{C}_{gp}$, $\overline{C}_k$, $\overline{C}_{op}$ — specific cost of 1 m of drainage, collectors and canals;

l, $\overline{l}_{op}$ — specific length of collectors and laterals, m/ha;

Φ_{op} — cost of water resources formation (including capital investments and annual costs within a given basin) is equal to the product of water volume per 1 ha by specific cost of water resources formation.

This value is given in reference.(7)

The volume of water per 1 ha, i.e., water application rate equals as follows:

$$\frac{O_p}{\eta_c}\,(1+\beta)$$

where O_p — net irrigation rate (f.o.b.—water release to a field);

η_c — system's efficiency;

β — leaching requirements.

Stemming from irrigation requirement per 1 ha and duration of water applications, the irrigation module, q_{op}, is determined; a_M, a_m, a_{op} —

depreciation costs of drainage, collectors and irrigation network, respectively; n—factor of normative efficiency, equalling 0.12 in land improvement;

m, m_1, m_{op} — operational costs of drainage, collecting and irrigation networks, respectively, i.e., shares of capital costs;

H_{TP} — depth of drainage construction by means of a drain layer (in the Golodnaya Steppe the depth equals 3 m when using a drain-layer—ЭD-3);

q_{gp} — drainage modulus, l/s ha;

$a, b, g, \overline{Q}$ — constants, dependent on the drainage construction method (in the Golodnaya Steppe, at $H_{TP} = 3.0$ m, these are equal, respectively, to 3.5 roubles, 0.06, 5 and 16.6 roubles per 1 l/s ha;

$\overline{\gamma}$ — constant for collectors, equalling 0.29 for the conditions of the Golodnaya Steppe;

m — slope angle for collectors;

$\overline{Q}_{op}$ — specific cost of an irrigation network, determined as described in our work(7) depending on the canal cost per unit of discharge and length Q_{op}, specific modulus, q_{op}, and network efficiency, η_c.

Drainage modulus, q_{gp}, is derived from the ground-water balance equation:

$$q_{gp} = \frac{[O_p(1-\eta_{mn})\,d_2' + \beta O_p] + \dfrac{O_p(1-\eta_c)\,d_2'' + O_c a + (\overline{\Pi} - \overline{O})}{\eta_c}}{t_{fer}} \qquad (18)$$

where, d_2'' — share of ground-water infiltration recharge resulting from losses from the irrigation network, parts of unit;

$\overline{\Pi}$-$\overline{O}$ — ground-water inflow-outflow per 1 ha;

t_{fer} — duration of vegetation, s.

It should be pointed out though that according to one of the popular formulas, for example, A.N. Kostyakov's formula, the drainage modulus should be equal to water intake capacity:

$$q_{gp} = \frac{\pi K(H_{gp} - h_i)}{B(\ln \dfrac{2B}{\pi D} + \Phi)} \qquad (19)$$

where, H_{gp} — drainage depth, m;

h_i — ground-water depth, m, derived from relationship (9);

B — drain space, m;

D — drainage diameter, m;

Φ — entrance resistance.

During vegetation moisture reserves should remain close to 0.

Precipitation occurred during this time in the arid zone, can be neglected; irrigation requirements are met by irrigation and ground-water input. Hence:

$$O_p \,.\, \eta_{mn} + (U+E)_i = U_o K_i \tag{20}$$

where, U_o — potential evapotranspiration;

K_i — coefficient of changing total evaporation relative to U_o, depending on the ground-water table (this coefficient is determined using the experimental data).

Then, inserting expression (7) in formula (20), we obtain;

$$U_o = \frac{O_p \,.\, \eta_{mn}}{K_i - 1 + \frac{h_i}{h_k}} \tag{21}$$

$$(U+E)_i = \frac{O_p \,.\, \eta_{mn}\left(1 - \frac{h_i}{h_k}\right)}{K_i - 1 + \frac{h_i}{h_k}} \tag{22}$$

Cancelling the equation of salt balance of the aeration zone by O_p, we obtain:

$$\beta = \frac{\eta_{mn} \,.\, C_{op} + \eta_{mn} \frac{h_k - h_i}{K_i \,.\, h_k - h_k + h_i} C_{2f}}{C_u} - (1 - \eta_{mn})\, d_2 \tag{23}$$

Thus, optimization of function (13) and equations (18), (19), (21), (23) permits the determination of the drainage depth (h_{gp}), ground-water depth (h_i), leaching share of irrigation (β), irrigation requirements (O_p) and drainage modulus (q_{gp}), the combination of which complies with the minimum of the function:

$$\Pi = f(O_p;\, q_{gp};\, \beta;\, h_{gp};\, h_i),$$

Assuming the ground-water depth ranging from 1 to 5 m at 0.5 m intervals and the drainage depth being within 2.5 to 4.0 m, the minimum of the function for given conditions is determined for each value of ground-water salinity.

The solution of the above equations using computers, resulted in the values of parameters of optimal land improvement regimes for the conditions of the Golodnaya Steppe at $h_k = 3.8$ m (Table 5).

Total water use meant for leaching and irrigation is in good agreement with the values given in Table 5.

Thus, determination of irrigation system's parameters, accounting for the determination of the optimal land improvement regime and minimization of overall costs, proves—in the main—the correctness of earlier studies made by Soviet pedologists-reclamationists, namely: ground water

TABLE V

Item	Ground-water salinity, C, g/l					
	1	2	3	5	10	15
Ground-water depth, m	2·0	2.5	2.5	3.0	3.5	3.5
Drainage depth, m	3.5	4.0	4.0	4.5	4. 5	4.5
Water delivery for irrigation, 1000 m³/ha	2,650	3,470	4,230	5,850	6,450	6,500
Incl. leaching requirements, 1000 m³/ha	950	1,200	1,960	1,750	500	600

salinity equalling 1-3 g/l, ground-water depth is to be 2.0-2.5 m; ground-water salinity equalling 5 g/l and more, the depth is to be 3.0-3.5 m.

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