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Evaluation of formulas developed for calculating the volume of water for leaching and their adaptation to the international assessment of soil salinity by electrical conductivity

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Abstract. The study analysed the formulas for calculating leaching rates adopted in the regulations of CIS countries during the period of mass development of new land areas for irrigation. An assessment was made of the applicability of the formulas of renowned scientists S.F. Averyanov and V.R. Volobuev to modern conditions, including an assessment of soil salinity according to the international classification. It was revealed that the formula of A.E. Nerozin is closest to the FAO balance approaches and to the results of experimental washings. It was established that the ratio of the percentage reduction in soil salinity by leaching in the 0-60 cm layer for the total amount of salts, ECe, and for the chloride ion is 0.7. This is taken into account in the form of adjustments to the salt leaching factors used in the formula. To calculate the share of water for displacing salts in the formula of A.E. Nerozin, it is recommended to use the empirical equation of specific water consumption per unit of reduction in ECe.

1 Introduction

In the desert zone of Uzbekistan, where irrigated lands are primarily susceptible to salinization, crop germination is impossible without leaching the saline soils. Leaching requires significant water expenditure. Determining the volume of water required for leaching is crucial for efficient farming and the rational use of scarce water resources. According to the World Resources Institute, Uzbekistan is among 33 countries at risk of extreme water stress by 2040. By that time, the country could experience chronic water shortages equivalent to 25-40% of current consumption. The forecast for 2050 is also bleak: the expected shortage is estimated at 12-15 billion m^3/year [1].

Given the aforementioned forecasts for reduced river flow due to climate change, Uzbekistan is implementing a number of water conservation measures (implementing water-saving technologies, concreting canals, strengthening water metering and water use management, and providing economic incentives for water users to adopt advanced technologies). To optimize water consumption for leaching, the digitalization of these

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processes requires a reliable calculation relationship for determining the volume of water for flushing, taking into account current conditions (water shortages, provision of fields with drainage, the possibility of operational calculations with a minimum of additional labor costs).

1.1 A brief description of international approaches to the leaching process and domestic formulas for determining leaching rates and their evaluation

In international theory, the fundamental concept of soil salinity regulation is the method of reducing soil salinity during the growing season for a specific crop, based on the principle of a leaching irrigation regime (LR leaching requirement, LF - leaching fraction), taking into account the mineralization of the irrigation water [2]. Drainage must be ensured [3 - 7]. These same sources, for successful leaching of salts from the soil, mention the importance of the water infiltration rate into the soil, which should not be too low or too high. Also mentioned as an option is the possibility of leaching the soil with precipitation [7, 8] and the advisability of special soil loosening to enhance infiltration.

The paper [8] notes that “there are several shortcomings in the LR concept as proposed using steady-state analysis. The LR concept is based on achieving maximum yield. Maximum yield may not be economically optimal. This is especially true when only saline waters are available and the potential maximum yield is not possible.” Advances in irrigation technology, such as micro-irrigation and sprinkler systems, make it possible to irrigate with very low leaching fractions (LF). However, irrigation with low leaching fractions can lead to soil salinization, which will reduce crop yields. In the era of computerization, transient state models do not calculate LR directly. Instead, models are simulated for a series of seasonal irrigation applications, from which the lowest water application that maintains the maximum yield is selected.

In domestic land reclamation science, many relationships have been developed for determining the volume of water required for leaching (formulas by A.N. Kostyakov, L.P. Rozov, S.F. Averyanov, V.R. Volobuev, I.S. Rabochev, A.E. Nerozin, and others). Almost all formulas, except those by V.R. Volobuev and I.S. Rabochev, take into account soil properties such as soil bulk density, maximum field capacity, and soil moisture before leaching. In the formulas by A.N. Kostyakov, L.P. Rozov, S.F. Averyanov, and A.E. Nerozin, the volume of water required for leaching consists of a portion of water used for soil saturation (to dissolve salts) and a portion used for displacing salts from the soil. The FAO methodology for calculating the volume of water for leaching using the balance model studied by us takes into account the leaching of salts by reducing the electrical conductivity ECe of the saturated soil extract ECe, in accordance with the international classification of soil salinity assessment.

This study analyzes formulas traditionally used in land development in Uzbekistan. Below are the main known empirical formulas for calculating the volume of water for leaching, used in regulatory documents for calculating soil leaching [9, 10].

S.F. Averyanov's formula [9] is a theoretically sound formula:

$$N = 10000 \text{ x } (2A \text{ x } \sqrt{D^*} \text{ x } t + h) \text{ x } m \qquad (1)$$

where,
t – is the duration of leaching (days);
h – estimated desalination depth (m);
m – soil porosity (as a percentage of volume);

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D* – coefficient of convective “filtration” diffusion, taking into account the peculiarities of salt transfer in soils (m^2/day). According to field experimental production studies, D* ~ (1 – 5) 10–2 m^2/day;

A – is a coefficient, the value of which is determined depending on the required degree of soil desalination calculated according to a special table, n is the permissible salt content (%) at a depth h;

n_0 – is the initial salt content of the soil in layer h (%);

n_1 – mineralization of water (%).

m – is the soil porosity as a percentage of its volume.

This formula is obtained for the case when the initial salinization is uniform along the profile. Therefore, when calculating leaching, salt reserves must be averaged within the calculated desalination depth.

Quote from source [9] “Often, methods for calculating the volume of water for leaching are empirical in nature and contain coefficients that are not essentially constant. The movement of moisture and salts in soils is a complex physicochemical process. With a single change of soil solution, the amount of salt displacement is always less than 100%. In sands, up to 90% is leached, in silty loams - up to 80% and in aggregated loams - up to 60%. The reasons are that, along with the displacement of free saline solution, salt transfer occurs in the through pores of the soil as a result of concentration differences (diffusion transfer), as well as dissolution of salts of the solid phase and exchange of the saline solution located inside the aggregates. Depending on the nature of the soil structure, the filtration rate and the composition of salts, one or another transfer process predominates.

Formula of V.R. Volobuyev [10]:

$$M = 10000 \text{ x } \alpha \text{ x } \lg \text{ (Sinitial / Sfinal)} \quad (2)$$

where M – is the volume of water for leaching, m^3/ha;

Sh – the salt content in the soil layer requiring leaching, in % of the soil mass;

So – permissible salt content in this layer, in % of the soil mass;

The salt release index α is an integral indicator of the leaching of salts from soils, depending on the mechanical composition of the soil and the chemical composition of soil salts.

In the author's tabular data, they are: 1.0 - 1.3 for light and medium loamy (slightly compacted) soils; 0.92 - 1.48 for medium loamy soils; 1.2 - 1.8 for medium and heavy loamy (dense) and layered soils; and 1.5-2.4 for clay soils or layered soils with clays (the first number is for soils of the sulfate-chloride type of salinity, the second is for chloride-sulfate). For heavily gypsumed soils, it is recommended to multiply the salt release indicators by 1.2.

Leaching rates can be calculated from the tabular salt release indices, but only as a rough guide. To refine the salt release indices for specific soil conditions, leaching tests are necessary.

A.E. Nerozin's formula has the form [10]:

$$M = (\Pi - m) + S/K - A + n \quad (3)$$

M – is the volume of water for leaching, m^3/ha;

P – field moisture capacity of the calculated soil layer (water requirement for dissolving salts), m^3/ha;

M – is the moisture content of the same soil layer before leaching, m^3/ha;

S/K – water requirement for displacing salts, m^3/ha;

S – is the amount of chlorine subject to leaching of salts from the calculated soil layer, m3/ha;

K – is the coefficient of leaching action of water (for chlorine), kg/ha 1 m^3 of water.

The values of the coefficient K are given in a special table compiled by the author (Table 3, left part). Depending on the degree of initial salinization, the mechanical composition of the soil and the drainage conditions of the site (the depth of groundwater), it varies from 1.0 to 5.0, increasing with increasing mechanical composition, increasing the degree of soil salinization and the depth of groundwater.

A - precipitation entering the soil during the period from the start of leaching to sowing, m^3/ha;

n – water loss due to evaporation over the same period, m^3/ha.

The amount of salts (chlorine) that must be leached from the soil is determined by the following calculation:

$$S = 100 \text{ x } h \text{ x } \alpha \, (zi - z_f) \text{ x } 1000 \tag{4}$$

where:

S – is the amount of salts (chlorine) to be leached from the reference soil layer, kg/ha;

h is the reference soil layer, m;

α– volume mass of the soil, g/cm^3;

$zi - z_f$ is the initial (before leaching) and permissible (after leaching, before sowing) chlorine content in the soil, as a percentage of the mass;

1000 is the multiplier for converting tons to kilograms.

From the above formulas it is clear that each of them corresponds to certain conditions and has some averaged table coefficients intended for the design of capital flushing and water consumption for large areas in the presence of artificial drainage.

For specific soil reclamation conditions, these coefficients require clarification. Consequently, the formulas considered have their limitations in application, given the high labor-intensive nature of additional soil studies.

Despite its theoretical significance, a significant limitation of the practical use of S.F. Averyanov's formula [9] is the need to determine the D* coefficients in field conditions through special studies (it is recommended to determine them on soil monoliths). V.R. Volobuev's formula [10] is characterized by a wide range of coefficients-salt release indicators for specific soil-reclamation conditions-and, as a rule, requires clarification.

One of the limiting factors in the application of the described formulas is the mandatory performance of soil analyses to determine the initial and final salt content in the soil in % by mass, which complicates the efficiency of obtaining data for calculating the volume of water for leaching.

Thus, in the above-described dependencies there are special tables of salt leaching coefficients developed by the authors. However, the coefficients given in the tables are not universal and it is advisable to refine them by testing using leaching of saline soils under specific conditions, in specific areas. This is due to the fact that the magnitude of salt release is influenced by: the degree of soil salinization, the characteristics of the chemical composition of soil salts, and, most importantly, the filtration coefficient, which, in addition to the mechanical composition of the soil and the depth of groundwater, is affected by the content of gypsum, carbonates that compact the soil, etc.

Recently, the Melioration Service of the Ministry of Water Resources of the Republic has been using the internationally accepted method of electroconductometry to measure soil and water salinity. This method allows for rapid, on-site quantitative determination of soil salinity (in ECe, dS/m), for example, on a farm, and, consequently, more accurate determination of the volume of water for leaching. To make an informed decision on leaching a site after an electroconductometry survey, refined recommendations for determining the volume of water for leaching are necessary.

Determining the volume of water for leaching based on soil salt survey data and soil salinity assessment using electrical conductivity measurements is possible, as the electrical conductivity method is successfully used in soil salinity monitoring within the Ministry of Water Resources of the Republic of Uzbekistan. The relationship between the electrical conductivity of the saturated soil extract and the total content of salts and chloride ion for the conditions of the Syrdarya region of Uzbekistan is shown in the graphs (Fig. 1 and 2). This relationship will depend on the amount and type of toxic salts in the soil (the chemistry of soil salinity: the predominance of chlorides or sulfates).

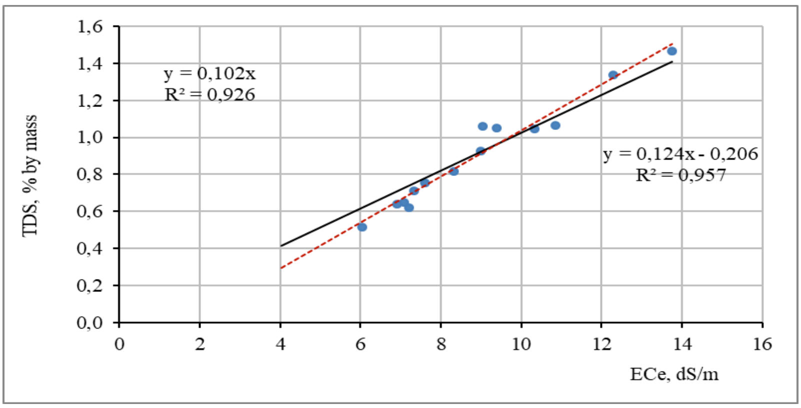

Fig. 1. Relationship between total salt content and electrical conductivity of saturated soil extract ECe.

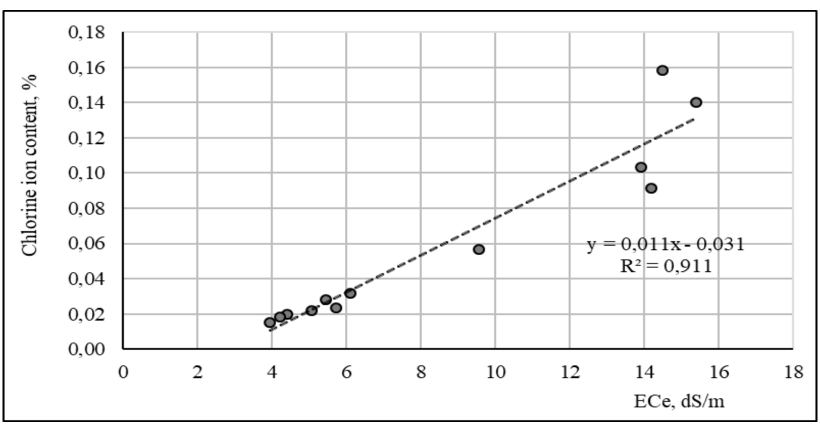

Fig. 2. Empirical relationship between the content of chlorine ion and the electrical conductivity of the saturated soil extract ECe.

From Figures 1 and 2 it is evident that, for the soil conditions of the Syrdarya region, there are high correlations between the electrical conductivity of the saturated soil extract ECe, both with the total salt content and with the chloride ion content. The graphs provided allow the determination of the total salt or chloride ion content (expressed as % by mass) based on ECe measurements.

The aim of the research is to provide scientific and experimental justification for the application (adaptation) of the domestic formula of E.A. Nerozin for calculating the volume of water for leaching using the assessment of saline soils according to the FAO classification for the electrical conductivity of the saturated soil extract ECe.

2 Materials and methods

Analysis of calculation relationships for determining the volume of water for leaching based on a review of published studies. Selection of a calculation relationship for testing.

Of the domestic relationships for calculating the volume of water for leaching, A.E.Nerozin's formula is suitable, as it has previously been tested using experimental leaching data and has demonstrated high convergence. It includes soil and climatic parameters (soil moisture and total water capacity, precipitation, and evaporation during the leaching period).

Analysis of available laboratory experimental databases: on the water-physical properties of soils in Uzbekistan and on leaching (salt leaching efficiency), statistical processing of experimental leaching data, calculations in Excel. Comparison of salt leaching by chloride ion and by ECe reduction. Refinement (adjustment) of salt leaching coefficients by comparing chloride ion leaching and ECe reduction based on experimental leaching data. Using empirical dependencies: the relationship of ECe with the total amount of salts (dense residue, %) and with the content of chloride ion (Fig. 1 and 2), as well as the dependence of specific water consumption on the degree of initial soil salinity (Fig. 4).

3 Results and discussion

The FAO methodology for calculating the volume of water required for leaching takes into account the electrical conductivity of the saturated soil extract (ECe) (actual and permissible), the volume of drainage runoff, the electrical conductivity of irrigation and drainage water, soil moisture, saturation percentage, and the depth of the desalinated layer [11].

Of the domestic models, the formula of A.E. Nerozin [10] is the most consistent with this approach, which takes into account:

– The mechanical composition of soils through field moisture capacity and volume mass;

– Initial moisture content;

– Initial and final salinization through the amount of salts to be leached out;

– The groundwater level, through the coefficient “K” of salt displacement, determined empirically;

– Meteorological indicators during the leaching period (precipitation and evaporation).

An analysis of multiple domestic calculation formulas for determining the volume of water for leaching, comparing experimental and calculated data, demonstrated sufficient reliability. As can be seen, the formula takes into account virtually all soil parameters and meteorological conditions, as well as the groundwater level (through soil moisture before leaching). Using the SoyuzNIHI hydromodular zoning system, which takes into account soil texture and groundwater level, operational leaching rates were calculated for average and long-term meteorological conditions, taking into account desalination of the 0-50 cm layer to a chlorine content of 0.02%.

Based on a comparison of various domestic formulas with experimental data, it was concluded that A. E. Nerozin's formula is the best for moderately and highly saline soils. When summarizing the actual data on the effectiveness of field leaching by different authors (with an initial degree of salinity from very strong to weak, loamy soils in different regions of Uzbekistan), a high convergence of the leaching results with the calculated values of the volume of water for leaching was established.

To use the formula of A.E. Nerozin, with the application of the international assessment of salinity based on the results of measuring the electrical conductivity of the saturated soil extract ECe, dS/m (Table 1), it became necessary to modify it. This is also important given that in irrigated lands, during the period after land development, the content of chloride ions has decreased, and sulfate salts predominate in the soil (Fig. 3).

Table 1. International and domestic classifications of soil salinity assessment according to ECe and chloride ion content.

Degree of soil salinization	ECe, dS/m [11]	by Cl', % [10]
Not salted	0-2	< 0.02
Slightly saline	2-4.	0.02-0.035
Moderately saline	4-8.	0.035-0.07
Highly saline	8-16.	0.07-0.14
Very heavily salted	>16	> 0.14

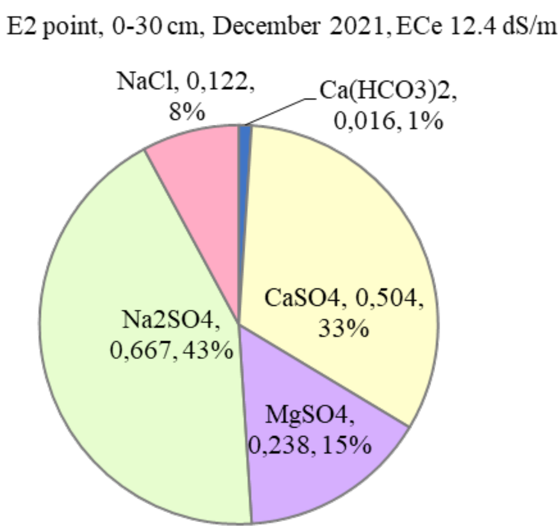

Fig. 3. Hypothetical composition of salts in the experimental area.

As noted above, experimental data from leaching saline soils in check plots has established a pattern of salt leaching from the soil (Figure 4). Figure 4 reflects the specific water consumption required to reduce soil salinity, m3/ha per 1 dS/m.

Experimental data show that, even under the most favorable conditions (ensuring water drainage and supplying large volumes of water for leaching), desalination of soil in the 0-70 cm layer is only possible by 60-80% of the initial salinity (Table 2).

According to the data of experiments in the Syrdarya region of Uzbekistan, on homogeneous light and medium loamy soils with a granulometric composition, with a high degree of salinity (more than 16 dS/m), the specific water consumption is: 480-500 m3/ha to reduce salinity by 1 dS/m, with an average degree of salinity (8 dS/m). 800 - 1000 m3/ha per 1 dS/m, and with an initially low degree of soil salinity (4 dS/m) more than 2000 m3/ha per 1 dS/m (Data from scientific reports of the Research Institute of Irrigation and Water Problems).

Adaptation of the calculation of the volume of water for leaching using A.E. Nerozin's formula to the international classification of soil salinity was carried out using two methods.

Method 1 – is based on determining the volume of water required to displace salts by converting the chlorine leaching coefficient KCl into the soil salinity reduction coefficient KES according to ECe, taking into account the total salt content.

Method 2 – using an empirical equation for the specific water consumption to reduce soil salinity by 1 dS/m (S/KCl – water consumption for leaching chloride ion from the calculated soil layer (kg/ha); S/KEC – water consumption to reduce soil salinity by leaching according to ECe, dS/m).

The results of experimental data processing on leaching saline soils in the Syrdarya region are partially shown in Table 2.

The results of experimental data processing on leaching saline soils in the Syrdarya region are partially shown in Table 2.

Table 2 shows that, with 4000 m³/ha of water applied to leaching using the check technology and adequate drainage, salt leaching in moderately saline loamy soils is no more than 60-65%.

Moreover, chlorine leaching in the 0-70 cm soil layer is more effective than reducing the total salt content by ECe. The ratio of soil salinity reduction by ECe to chloride ion content (as a percentage of the original content) was 0.70 (Table 2). Statistical analysis confirmed this ratio (Table 2).

Table 2. Results of statistical processing of the results of chlorine ion leaching and ECe reduction in the 0-70 cm layer based on the results of washing with water volumes of 4000 m^3/ha in the Syrdarya region.

Statistical processing indicators	Chlorine ion leaching percentage	Percentage reduction of ECe	Ratio: ECe / chlorine
Average	**-63.1**	**-44.0**	**0.70**
Dispersion	38.76	68.93	
Observations	8.00	8.00	
Pearson correlation	0.68		
Hypothetical difference in means	0.00		
df	7.00		
t- statistics	**-8.86**		
P(T<=t) one-sided	0.00		
t critical one-sided	1.89		
P(T<=t) two-sided	0.00		
t critical bilateral	2.36		

* Paired two-sample t-test for means

Using this ratio, new leaching coefficients of the total amount of salts were obtained based on soil ECe measurement data, KEC (Table 3). We used this indicator in the first version of the formula modification. The KEC coefficient can be taken from Table 3.

The modification of the formula based on the first method consists of changing (converting) the chlorine leaching coefficients (kg/m³ of water) in A.E. Nerozin's formula to KEC by multiplying the KCl coefficient (according to A.E. Nerozin) by 0.7 (Table 3).

When calculating the water consumption for leaching salts S, in this case, the graph in Figure 4 can be used as an auxiliary material.

In the second method (variant), a modification of the formula, the volume of water for leaching salts is determined as the required (specified) reduction in soil salinity by ECe (ΔECe), multiplied by the specific leaching water consumption required to reduce salinity in the 0-60 cm soil layer by 1 dS/m (see Figure 4).

The specified amount of salts leached by leaching is expressed as the difference between the initial and final (specified) ECe values (ΔECe).

Table 3. Leaching coefficients of salts K for chlorine in the formula of A.E. Nerozin and their refinement when assessing soil salinity by ECe).

Indicators according to Nerozin E.A (K_{Cl}) [10]					Coefficients adjusted according to ECe dS/m **(K_{EC})**				
Chlorine content before washing in the 0-100 cm layer, %	Average content	Chlorine leaching coefficients (kg/m³ of water), at the depth of groundwater before leaching, m			ECe dS/m before flushing in the 0-60 cm layer	Average	ECe change coefficients dS/m, at groundwater depth before leaching, m		
		1.5	2.5	3.5			1.5	2.5	3.5
Soils of average mechanical composition					Soils of average mechanical composition				
0.04…0.1	0.07	1.3	2.1	3.8	8 - 13	10.5	0.9	**1.5**	2.7
0.1…0.2	0.15	2.2	3.3	5.0	13 - 17	15.0	1.5	2.3	3.5
Soils with heavy mechanical composition					Soils with heavy mechanical composition				
0.04…0.1	0.07	1	1.5	2.9	8 - 13	10.5	0.7	1.1	2.0
0.1…0.2	0.15	1.8	2.6	4.0	13 - 17	15	1.3	1.8	2.8

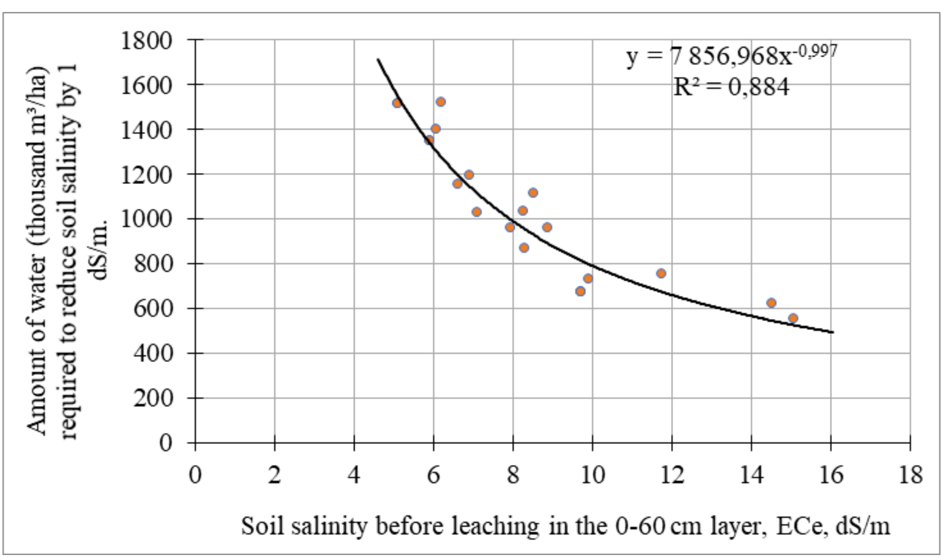

Fig. 4. Dependence of the specific leaching water consumption for reducing soil salinity by 1 dS/m, depending on the initial degree of salinity for the conditions of the Syrdarya region.

Since the calculation using the first method (using the leaching coefficient K) assumes soil desalination by chloride ion, the second method is preferable as it is simpler: it directly utilizes the international classification for assessing soil salinity according to ECe. The empirical equation shown in Figure 4 was derived from ECe measurements.

Therefore, the formula is adapted to the international classification for assessing soil salinity according to ECe and can be used to calculate the volume of leaching water based on salinity survey data conducted by land reclamation expeditions in Uzbekistan.

4 Conclusion

1. A review and analysis of previously developed and used formulas by renowned scientists S.F. Averyanov and V.R. Volobuev was conducted. Their applicability to current conditions was assessed.

2. Based on the results of experimental leaching, it was established that A.E. Nerozin's formula is closest to the FAO balance approaches and is suitable for adaptation to the international classification of soil salinity according to ECe.

3. Two methods for determining water consumption for leaching salts from soil according to ECe are substantiated: introducing corrections to the author's coefficients and using an empirical relationship using two methods:

- The possibility of using refined salt leaching coefficients based on ECe values was established by converting the chlorine leaching coefficient KCl in the author's table;
- A method for calculating the volume of water for leaching using the same formula is proposed, using an empirical equation for the specific water consumption for reducing soil salinity by 1 dS/m.

The application of the formula for calculating the volume of water for leaching and establishing the leaching requirement for the farm as a whole based on soil salinity measurement data based on ECe values is scientifically substantiated.

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