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IMPROVEMENT OF THE METHODOLOGY FOR ASSESSING THE QUALITY OF IRRIGATION WATERS FOR THE DANGER OF SOIL SALINIZATION

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The relevance of the article is based on the problems of irrigation of agricultural land in the south of Ukraine: the limitation of water resources of irrigation quality; unevenness of their location; the formation of artificial reservoirs that do not meet the expected design conditions. In addition, current methods of assessing the quality of irrigation water often give general recommendations that are difficult to use in practice. The purpose of the work is to improve the methodology for assessing the quality of irrigation water according to the risk of soil salinization in DSTU 2730:2015. The object of research is the mineral composition of irrigation water. The subject of the study is the evaluation of the properties of irrigation water depending on the ratio of the main ions.

The article provides an analysis of methods for assessing the irrigation properties of water. Consider the shortcomings of the DSTU 2730:2015 methodology, which are the general nature of the recommendations for calculating the amount of toxic salts in chlorine equivalents, as well as the fact that hydrogen carbonate ions can be as toxic as carbonate ions due to the formation of baking soda in water. An analysis of the water typification of V.K. Khilchevskii is provided.

based on the basic classification of natural waters Alokina O.A. It is shown that some water subtypes in the classification of V.K. Khilchevskii cannot exist in nature. A detailed typification of irrigation waters based on the typification of natural waters by O. A. Alokina is proposed. Suggestions for eliminating the shortcomings of the DSTU 2730:2015 methodology are provided based on the proposed detailed typification of irrigation water, as well as the formula for calculating the amount of toxic ions in chlorine equivalents for different subtypes of irrigation water with examples of calculations. An analysis of the possibility of irrigation salinization of the soil when using the waters of the Dniester, Danube, and Sarata rivers, as well as the Sasyk, Kuchurganske, and Baraboyske reservoirs for irrigation, was performed. It is shown that the waters of the Dniester and Danube rivers, as well as the Baraboy reservoir, without the threat of irrigation salinity, are suitable for irrigation of all types of soil. The waters of the Sarat River contribute to the salinization of all types of soil. The waters of the Sasytskyi and Kuchurganskyi reservoirs require a careful approach when irrigating easily permeable soils; when irrigating poorly permeable soils, the probability of salinization is high.

Key words: water quality, detailed typification, toxic ions, chlorine equivalent, irrigation salinization.

Юрасов С.М., Караулов В.Д. Удосконалення методики оцінки якості зрошувальних вод на небезпеку засолення ґрунтів

Актуальність статті обґрунтовано проблемами іригації сільгоспугідь півдня України: обмеженістю водних ресурсів іригаційної якості; нерівномірністю їх розташування; утворенням штучних водойм, яки не відповідають очікуваним проектним кондиціям. Крім того, діючи методики оцінки якості іригаційних вод часто дають загальні рекомендації, якими важко користуватися на практиці. Мета роботи полягає у вдосконаленні методики оцінки якості іригаційних вод за небезпекою засолення ґрунту в ДСТУ 2730:2015. Об'єктом дослідження є мінеральний склад іригаційних вод. Предметом дослідження являється оцінка властивостей іригаційних вод в залежності від співвідношення головних іонів.

У статті надається аналіз методик оцінки іригаційних властивостей вод. Розглянуті недоліки методики ДСТУ 2730:2015, яки полягають в загальному характері рекомендацій розрахунку суми токсичних солей в еквівалентах хлору, а також в тому, що гідрокарбонат-іони можуть бути такими ж токсичними, як і карбонат-іони, завдяки утворенню у воді питної соди. Надається аналіз типізації вод Хільчевського В.К. на основі базової класифікації природних вод Альокіна О.А. Показано, що деякі підтипи вод в класифікації Хільчевського В.К. не можуть існувати у природі. Запропоновано детальна типізація іригаційних вод на основі типізації природних вод Альокіна О.А. Надані пропозиції усунення недоліків методики ДСТУ 2730:2015 на основі запропонованої детальної типізації іригаційних вод, а також формули розрахунку суми токсичних іонів в еквівалентах хлору для різних підтипів іригаційних вод з прикладами розрахунків. Виконан аналіз можливості іригаційного засолення ґрунту при використанні для поливу вод річок Дністер, Дунай і Сарата, а також водосховищ Сасик, Кучурганське та Барабойське. Показано, що води річок Дністер і Дунай, а також Барабойського водосховища без загрози іригаційного засолення придатні для поливу усіх типів ґрунтів. Води р. Сарата сприяють засоленню усіх типів ґрунтів. Води Сасицького і Кучурганського водосховищ потребують обережного підходу при поливі легкопроникних ґрунтів, при поливі важкопроникних ґрунтів ймовірність засолення велика.

Ключові слова: якість вод, детальна типізація, токсичні іони, еквівалент хлору, іригаційне засолення.

Entry. The problem of irrigation of farmland in the south of Ukraine was and remains very relevant: today decisions are being made on the reconstruction of networks of some soviet irrigation systems (for example, "Nizhnednistrovskaya" [1]); the limited water resources of irrigation quality and the unevenness of their location makes it necessary to form artificial reservoirs for the accumulation of water for the purpose of their further use for irrigation (but the waters in these reservoirs often do not correspond to the expected design conditions [2]); acting methods for assessing the quality of irrigation waters often give general recommendations that are difficult to use in practice. For example, in the regulatory document [3, p. 7] in the formula for calculating the indicator of the amount of toxic ions in chlorine equivalents, all toxic bicarbonate ions have a coefficient of 0.4, but some of these ions in some cases may be part of baking soda,

the toxicity of which is the same as soda. In the above formula, ordinary soda has a coefficient of 5. In addition, the recommendations for the definition of toxic ions in this document are of a general nature. Therefore, the improvement of methods for assessing the quality of irrigation waters and the analysis of irrigation properties of water bodies is an urgent task.

The aim of the work is to improve the methodology for assessing the quality of irrigation waters for the danger of soil salinization in DSTU 2730:2015.

The object of study is the mineral composition of irrigation waters.

The subject of research is the assessment of the properties of irrigation water depending on the ratio of the main ions.

Assessment and classification of irrigation water quality. In [2], a detailed analysis of methods for assessing the irrigation properties of waters is given. Let us briefly dwell on this.

Irrigation classification of waters is established according to four criteria:

 – salt concentration;

 – the ratio of ions;

 – concentration of toxic elements that can adversely affect agricultural plants and the environment as a whole;

 – concentration of biogenes.

The most important are the first two criteria.

 Mineralization of natural waters is determined by: anions – chlorides (Cl^-), sulfates (SO_4^{2-}), carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-); cations – potassium (K^+), sodium (Na^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}). Often considered carbonates with bicarbonates, and potassium with sodium.

High mineralization of water during irrigation can lead to excessive accumulation of salts in the root layer of the soil. This is called salinization. Salts that inhibit or adversely affect agricultural plants, reduce the yield and its quality [4, p. 8], the following: Na_2CO_3, $NaHCO_3$, $NaCl$, $CaCl_2$, Na_2SO_4, $MgCl_2$, $MgSO_4$.

Kostyakov A.N. assesses the danger of soil salinization by the mineralization of irrigation water as follows:

 – up to 1.0 g/dm³ – suitable for irrigation;

 – from 1.0 to 1.5 g/dm³ – careful irrigation;

 – from 1.5 to 3.0 g/dm³ – analysis of the chemical composition of salts is necessary,

 – more than 3 g/dm³ – not suitable for irrigation [5, p. 48].

Soil salinization is also characterized by an indicator of toxicity. The maximum salt content, in which there is a inhibition of the development of crops, is called the toxicity threshold.

 Salts found in soil and water are presented in Table 1.

Salts on a gray background (Table 1) are harmful to plants. The most toxic of them are soda (regular – Na_2CO_3, drinking – $NaHCO_3$), sodium chloride and sulphate ($NaCl$ and Na_2SO_4), calcium chloride ($CaCl_2$). Magnesium sulfate and chloride ($MgSO_4$, $MgCl_2$) have the least toxicity.

Table 1

Toxicity of Basic Salts [4, p. 9; 6, p. 84; 7, p. 386]

NaCl	Na_2SO_4	Na_2CO_3	$NaHCO_3$
$MgCl_2$	$MgSO_4$	$MgCO_3$	$Mg(HCO_3)_2$
$CaCl_2$	$CaSO_4$	$CaCO_3$	$Ca(HCO_3)_2$

Toxicity of Kovda V.A. salts [7, p. 386] is arranged in the following sequence: $Na_2CO_3 > NaHCO_3 > NaCl > CaCl_2 > Na_2SO_4 > MgCl_2 > MgSO_4$.

In some sources (for example, [3, p. 4, 7; 8, p. 24]), the magnesium ion is always considered toxic, so the salts $MgCO_3$ and $Mg(HCO_3)_2$ are also classified as toxic (in Table 1 it is given in light gray color).

Salts dissolved in water are present in the form of ions. However, sometimes the suitability of water for irrigation is established by the content of salts in it [5, p. 49]: on well-permeable soils, the content of $Na_2CO_3 < 0.1\%$ (1 g/dm^3) is permissible; $NaCl < 0,2\%$; $Na_2SO_4 < 0,5\%$. Subject to the simultaneous presence of salts, these boundaries are reduced. If the majority of salts are $NaCl$ and Na_2SO_4, then the use of such water for irrigation is possible only on light or drained soils.

The main ions can be toxic and non-toxic. Toxic include ions capable of forming toxic salts. Cl^- and Na^+ ions are always toxic, the other main ions, depending on their mutual balancing, can be both toxic and non-toxic: Mg^{2+} and Ca^{2+} with Cl^- give toxic salts, and with CO_3^{2-} and HCO_3^- (according to Kovda VA) – non-toxic; CO_3^{2-} and HCO_3^- with Na^+ give the most toxic salts to plants [8, p.24]. The release of toxic ions is conveniently performed if we present the mineralization of water as a sum of hypothetical salts [5, p. 48, 49; 6, p. 84; 9, p. 201; 10, p. 67; 11, p. 389, 390].

Kostyakov A.N. [5, p. 48, 49] indicates that for waters with mineralization of $1.5–3.0 \text{ mg/dm}^3$, analysis of the chemical composition of salts is necessary.

Alokin O. A. believes that it is possible to get an idea of the composition of salts in water, if we conditionally assume that when water evaporates, salts will fall out when ions are combined in the following sequence: cations – Ca^{2+}, Mg^{2+}, Na^+; anions – HCO_3^-, SO_4^{2-}, Cl^- [11, p. 389, 390].

The sequence of combination of ions in the Hydrogeologist's Reference Manual [10, p. 67] is inverse: anions – Cl^-; SO_4^{2-}; ($CO_3^{2-} + HCO_3^-$); cations – ($K^+ + Na^+$); Mg^{2+}; Ca^{2+}. But, the composition of salts will be the same both in direct sequence and in reverse.

In DSTU 2730:2015 [3, p. 4, 7] the danger of irrigation salinization of the soil is estimated by the sum of toxic salts in chlorine equivalents $e(rCl^-)$. This amount is calculated by the formula:

$$e(rCl^-) = rCl^- + 0{,}2(rSO_4^{2-})_T + 0{,}4(rHCO_3^-)_T + 5rCO_3^{2-}, \qquad (1)$$

where rCl^- – amount of chlorides, mg-eq/dm^3; $(rSO_4^{2-})_T$ – amount of toxic sulfates, mg-eq/dm^3; $(rHCO_3^-)_T$ – amount of toxic bicarbonates, mg-eq/dm^3; rCO_3^{2-} – amount of toxic carbonates, mg-eq/dm^3.

The technique proposed in [3, p. 7] has disadvantages.

First, the recommendations for the definition of toxic ions are general in nature [3, p. 7] (Table 2). They are difficult to use in practice.

Table 2

Scheme of binding of ions into toxic and non-toxic salts (DSTU 2730:2015)

Ions	CO_3^{2-}	HCO_3^-	SO_4^{2-}	Cl^-
Ca^{2+}	–	2	5	8
Mg^{2+}	–	3	6	9
$Na^+ + K^+$	1	4	7	10

Secondly, formula (1) does not take into account the fact that bicarbonate ions can be as toxic as carbonate ions, due to the formation of baking soda in water ($NaHCO_3$).

Therefore, this part of the HCO_3^- ions in the formula (1) must be combined with CO_3^{2-} ions that form ordinary soda (Na_2CO_3) and have a coefficient of 5.

Elimination of these shortcomings is possible in determining the types of irrigation waters that have different sets of hypothetical salts, special (specific) for each type. In this case, it is possible for each type of water to provide its set of toxic ions and the calculated formula for the sum of toxic salts in chlorine equivalents.

The most common classification of natural waters is the classification of Alokin O.A. [11, p. 121] (Fig. 1), in which waters are divided into classes (according to the predominant anion), groups (according to the predominant cation) and types (according to the ratio of anions and cations).

In this classification, natural waters of the same type may have different sets of hypothetical salts.

In [12, p. 101], the classification of waters of Alokin O.A. is taken as basic and its detailing is proposed based on the content of the prevailing (class-forming) anion (Fig. 2): subtype a – anion content of more than 75% in equivalents; б – from 50% to 75%; в – less than 50%.

The scheme of improvement (Fig. 2) of the classification of natural waters of Alyokina O.A. has drawbacks and is not fully thought out by the authors.

Firstly, waters of sulfate and chloride classes, calcium or magnesium groups cannot be of the first type. In the basic classification of Alokin O.A. (Fig. 1) they are absent not
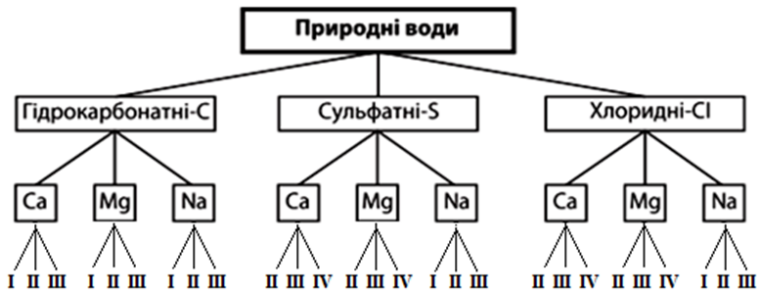

Fig. 1. Classification of natural waters according to Alokin O.A.
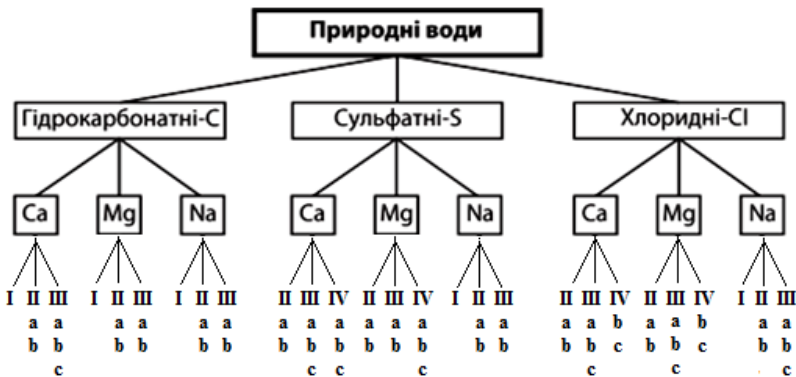

Fig. 2. Scheme of improvement [12, p. 101] of the basic classification
of natural waters of Alokina O.A.

by chance. Alyokin O.A. does not explain the reason for the absence of type I waters in the mentioned classes and groups of natural waters, however, this can be done using the equality of 100% of the sums of the concentrations of anions and cations in %-equivalent form and the ratio of ions in the types of natural waters according to Alokin O.A.:

$$(rHCO_3^- + rSO_4^{2-} + rCl^-) = (rCa^{2+} + rMg^{2+} + rNa^+) = 100\%; \qquad (1)$$
$$I - rHCO_3^- > (rCa^{2+} + rMg^{2+}) \quad \text{або} \quad rNa^+ > rCl^- + rSO_4^{2-}; \qquad (2)$$
$$II - rHCO_3^- \leq (rCa^{2+} + rMg^{2+}) \leq (rHCO_3^- + rSO_4^{2-}) \quad \text{або} \quad rCl^- \leq rNa^+ \leq rCl^- + rSO_4^{2-}; \qquad (3)$$
$$III - (rCa^{2+} + rMg^{2+}) > (rHCO_3^- + rSO_4^{2-}) \quad \text{або} \quad rNa^+ \leq rCl^-. \qquad (4)$$

Consider the statement – S^{Ca}_I, S^{Mg}_I, Cl^{Ca}_I and Cl^{Mg}_I waters do not exist.

In the accepted marks, the predominant ones are: anions – SO_4^{2-} or Cl^-; cations – Ca^{2+} or Mg^{2+}. Accordingly (1), only in the case of $rHCO_3^- < 50\%$ is there a possibility that either SO_4^{2-} or Cl^- may be predominant. Otherwise ($rHCO_3^- > 50\%$) even in the absence of one of the anions (rSO_4^{2-} or rCl^-), the second anion does not become predominant. In type I waters, the ratio (2) should be performed: $rHCO_3^- > (rCa^{2+} + rMg^{2+})$. It follows that $(rCa^{2+} + rMg^{2+}) < 50\%$, but then $rNa^+ > 50\%$, so it is predominant and determines the group of waters, that is, if sul-tulle or chloride waters of the first type, then it is only a sodium group: S^{Na}_I or Cl^{Na}_I. Thus, S^{Ca}_I, S^{Mg}_I, Cl^{Ca}_I and Cl^{Mg}_I are absent in natural waters due to the impossibility of such a ratio.

Secondly, in some groups of natural waters, the predominant anions cannot have the indicated concentration values. Or, in other words, some of the proposed subtypes (Fig. 2) are absent in natural waters, according to the detailed classification they have a different designation.

For example: waters of bicarbonate class, calcium or magnesium groups marked – $C^{Ca}_{Iв}$ or $C^{Mg}_{Iв}$ are actually – $C^{Na}_{Iв}$.

Let's show it. According to the detailed classification, the records of $C^{Ca}_{Iв}$ and $C^{Mg}_{Iв}$ denote: HCO_3^- – the predominant anion; б – $rHCO_3^- < 50\%$ of the total anion content; type I (ratio (3)) – $rHCO_3^- > (rCa^{2+} + rMg^{2+})$. It follows that the sum $(rCa^{2+} + rMg^{2+}) < 50\%$, then $rNa^+ > 50\%$, so it determines the group of waters. Thus, the waters of $C^{Ca}_{Iв}$ and $C^{Mg}_{Iв}$ do not exist, they have the designation – $C^{Na}_{Iв}$. Otherwise, in the waters of $C^{Ca}_{Iв}$ and $C^{Mg}_{Iв}$ there can be only $rHCO_3^- > 50\%$.

The second example, C^{Na}_{IIIa}: the predominant anion is $rHCO_3^-$; type III (ratio (5)) – $(rCa^{2+} + rMg^{2+}) > (rHCO_3^- + rSO_4^{2-})$; а – $rHCO_3^- > 75\%$. So $(rCa^{2+} + rMg^{2+}) > 75\%$, then $rNa^+ < 25\%$, hence it follows that the predominant cation is either rCa^{2+}, or rMg^{2+}, i.e. C^{Ca}_{IIIa} or C^{Mg}_{IIIa}. In waters of type C^{Na}_{III} there can be no $rHCO_3^- > 75\%$.

Next, we consider Cl^{Ca}_{IIa}, $Cl^{Ca}_{IIб}$, Cl^{Mg}_{IIa} and $Cl^{Mg}_{IIб}$. If in waters of chloride class $rCl^- > 50\%$ (б or а), then in waters of type II of this class with a characteristic ratio of $rNa^+ > rCl^-$, sodium is the predominant cation: $rNa^+ > rCl^- > 50\%$. This means that the ratio of ions Cl^{Ca}_{IIa}, $Cl^{Ca}_{IIб}$, Cl^{Mg}_{IIa} and $Cl^{Mg}_{IIб}$ are impossible, they have the designation Cl^{Na}_{IIa} or $Cl^{Na}_{IIб}$.

Now consider S^{Na}_{IIIa}. If in sulfate waters $rSO_4^{2-} > 75\%$ (а), then in type III waters of this class with a characteristic ratio of $rCl^- > rNa^+$ the sum $(rHCO_3^- + rCl^-) < 25\%$, hence it follows that $rCl^- < 25\%$, togdi and $rNa^+ < 25\%$, then sodium is not predominant. Waters with a ratio of S^{Na}_{IIIa} ions actually have the designation either S^{Ca}_{IIIa}, or S^{Mg}_{IIIa}.

Taking into account the above and taking into account that according to the basic classification of Alyokin O.A. in the sodium group of waters there is no fourth type, the scheme of detailed classification [12, p. 101] will have the following form (Fig. 3).

In this classification, waters of the same subclass may also have different sets of hypothetical salts. The mentioned deficiency can be eliminated if the types of natural waters I, II and III according to Alokin O.A. [11, p. 120] are divided into subtypes
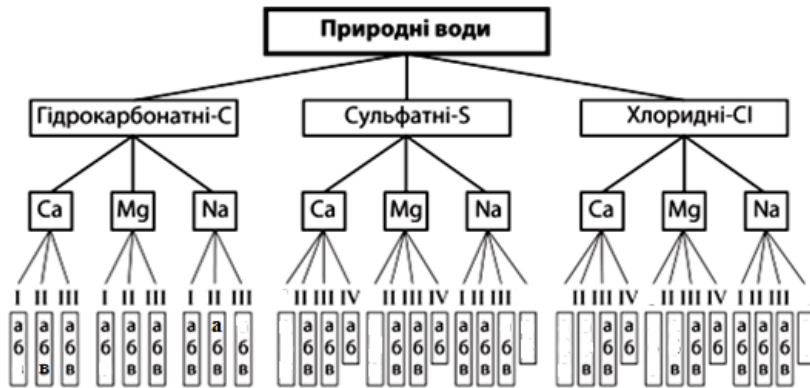
Fig. 3. Scheme of detailed classification taking into account the comments made

(I, IIa, IIb, IIIa, IIIb, IIIc) [2] according to the scheme in Fig. 4. In this case, each subtype will have its own specific set of hypothetical salts.

Type IV waters [11, p. 121] are not considered because it includes acidic marsh, mine and volcanic waters, as well as waters heavily polluted by industrial effluents that are not suitable for irrigation.

According to the mutual balancing of the main ions in the sequence outlined above, sets of hypothetical salts can be made for subtypes of waters:

I – $NaCl$, Na_2SO_4, $NaHCO_3$, $Mg(HCO_3)_2$, $Ca(HCO_3)_2$;

IIa – $NaCl$, Na_2SO_4, $MgSO_4$, $Mg(HCO_3)_2$, $Ca(HCO_3)_2$;

IIb – $NaCl$, Na_2SO_4, $MgSO_4$, $CaSO_4$, $Ca(HCO_3)_2$;

IIIa – $NaCl$, $MgCl_2$, $MgSO_4$, $Mg(HCO_3)_2$, $Ca(HCO_3)_2$;

IIIb – $NaCl$, $MgCl_2$, $MgSO_4$, $CaSO_4$, $Ca(HCO_3)_2$;

IIIc – $NaCl$, $MgCl_2$, $CaCl_2$, $CaSO_4$, $Ca(HCO_3)_2$.

It is convenient to estimate the amount of toxic main ions in water according to Table. 3.

Table 3: gray highlights the area of toxic salts (ions); in the cell of the table at the intersection of the column and the row is the concentration (mg-eq/dm³) of the ions in the water that make up the hypothetical salt (which balance each other and make up a hypothetical salt).
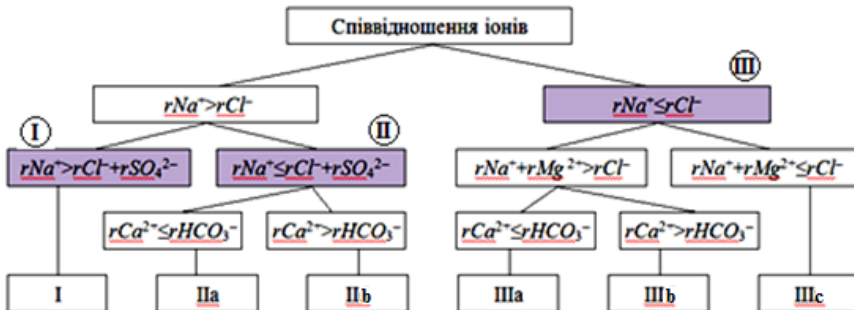

Fig. 4. Scheme of detailed typification of irrigation waters [2]

Table 3

The composition of hypothetical salts in different subtypes of water (the sequence of balancing of ions is taken from the Handbook manual of the hydrogeologist [10, p. 67])

Concentration of toxic salts, mg/dm³: $NaCl = 58{,}4 \times rCl^-$; $Na_2SO_4 = 71{,}0 \times rSO_4^{2-}$; $NaHCO_3 = 84{,}0 \times (rHCO_3^- - rCa^{2+} - rMg^{2+})$.				
Ion	rNa^+	rMg^{2+}	rCa^{2+}	Ratio (I)
rCl^-	rCl^-	0	0	$rCl^- + rSO_4^{2-} < rNa^+$ (або $rHCO_3^- > rCa^{2+} + rMg^{2+}$)
rSO_4^{2-}	rSO_4^{2-}	0	0	
$rHCO_3^-$	$rHCO_3^- - rCa^{2+} - rMg^{2+}$	rMg^{2+}	rCa^{2+}	
2) —"—: $NaCl = 58{,}4 \times rCl^-$; $Na_2SO_4 = 71{,}0 \times (rNa^+ - rCl^-)$; $MgSO_4 = 60{,}2 \times (rCl^- + rSO_4^{2-} - rNa^+)$.				
Ion	rNa^+	rMg^{2+}	rCa^{2+}	Ratio (IIa)
rCl^-	rCl^-	0	0	$rCl^- < rNa^+$ $rCl^- + rSO_4^{2-} \geq rNa^+$ $rHCO_3^- \geq rCa^{2+}$
rSO_4^{2-}	$rNa^+ - rCl^-$	$rCl^- + rSO_4^{2-} - rNa^+$	0	
$rHCO_3^-$	0	$rHCO_3^- - rCa^{2+}$	rCa^{2+}	
3) —"—: $NaCl = 58{,}4 \times rCl^-$; $Na_2SO_4 = 71{,}0 \times (rNa^+ - rCl^-)$; $MgSO_4 = 60{,}2 \times rMg^{2+}$.				
Ion	rNa^+	rMg^{2+}	rCa^{2+}	Ratio (IIb)
rCl^-	rCl^-	0	0	$rCl^- < rNa^+$
rSO_4^{2-}	$rNa^+ - rCl^-$	rMg^{2+}	$rCa^{2+} - rHCO_3^-$	$rCl^- + rSO_4^{2-} \geq rNa^+$
$rHCO_3^-$	0	0	$rHCO_3^-$	$rHCO_3^- < rCa^{2+}$
4) —"—: $NaCl = 58{,}4 \times rNa^+$; $MgCl_2 = 47{,}6 \times (rCl^- - rNa^+)$; $MgSO_4 = 60{,}2 \times rSO_4^{2-}$.				
Ion	rNa^+	rMg^{2+}	rCa^{2+}	Ratio (IIIa)
rCl^-	rNa^+	$rCl^- - rNa^+$	0	$rCl^- \geq rNa^+$
rSO_4^{2-}	0	rSO_4^{2-}	0	$rCl^- < rNa^+ + rMg^{2+}$
$rHCO_3^-$	0	$rHCO_3^- - rCa^{2+}$	rCa^{2+}	$rHCO_3^- \geq rCa^{2+}$
5) —"—: $NaCl = 58{,}4 \times rNa^+$; $MgCl_2 = 47{,}6 \times (rCl^- - rNa^+)$; $MgSO_4 = 60{,}2 \times (rNa^+ + rMg^{2+} - rCl^-)$.				
Ion	rNa^+	rMg^{2+}	rCa^{2+}	Ratio (IIIb)
rCl^-	rNa^+	$rCl^- - rNa^+$	0	$rCl^- \geq rNa^+$
rSO_4^{2-}	0	$rNa^+ + rMg^{2+} - rCl^-$	$rCa^{2+} - rHCO_3^-$	$rCl^- < rNa^+ + rMg^{2+}$
$rHCO_3^-$	0	0	$rHCO_3^-$	$rHCO_3^- < rCa^{2+}$
6) —"—: $NaCl = 58{,}4 \times rNa^+$; $MgCl_2 = 47{,}6 \times rMg^{2+}$; $CaCl_2 = 55{,}5 \times (rCl^- - rNa^+ - rMg^{2+})$.				
Ion	rNa^+	rMg^{2+}	rCa^{2+}	Ratio (IIIc)
rCl^-	rNa^+	rMg^{2+}	$rCl^- - rNa^+ - rMg^{2+}$	$rCl^- \geq rNa^+ + rMg^{2+}$ (або $rHCO_3^- + rSO_4^{2-} < rCa^{2+}$)
rSO_4^{2-}	0	0	rSO_4^{2-}	
$rHCO_3^-$	0	0	$rHCO_3^-$	

To convert the concentration of ions from an equivalent form (mg-eq/dm³) to a weight (mg/dm³), it is necessary to multiply their equivalent concentration by the corresponding coefficients, which have the following values: $CO_3^{2-} - 30.00$; $HCO_3^- - 61.02$; $SO_4^{2-} - 48{,}03$; $Cl^- - 35{,}45$; $Ca^{2+} - 20{,}04$; $Mg^{2+} - 12{,}15$; $Na^+ - 22{,}99$; $K^+ - 39.10$.

For each subtype of water in Table 3, formulas for calculating the concentration of hypothetical toxic salts in weight form are given.

The calculation of the salt concentration according to Table 3 will be considered on the example of waters of subtype I (Table 3(1)). $NaHCO_3$ baking soda is hypothetically present in water due to the mutual balancing of part of the Na^+ ions and part of the HCO_3^- ions. In equivalents, these parts are equal to ($rHCO_3^--rCa^{2+}-rMg^{2+}$). The weight concentration of the mentioned part of sodium ions is $22.99*(rHCO_3^--rCa^{2+}-rMg^{2+})$, and part of the bicarbonate ions is $61.02*(rHCO_3^--rCa^{2+}-rMg^{2+})$, hence the concentration of $NaHCO_3$ baking soda is $84.01*(rHCO_3^--rCa^{2+}-rMg^{2+})$.

Posokhov O.V., considering the typification of natural waters Alyokina O.A., proposed to divide the waters of type III into two subtypes: IIIa ($rNa^++rMg^{2+}>rCl^-$) and IIIb ($rNa^++rMg^{2+}<rCl^-$) [11, p.121]. Alyokin O.A. notes that subtype IIIb is characteristic of highly mineralized waters of lagoon origin.

Subtype IIIb according to Posokhov O.V. corresponds to the subtype IIIc in the proposed detailed typing. Natural waters of this subtype can be excluded from the list of waters suitable for irrigation. But, with artificial feeding of the reservoir, water suitable for irrigation can sometimes form with the ratio of ions according to subtype IIIc. For example, in the Sasyk reservoir, waters of this subtype were observed with a probability of 5% and had the lowest mineralization of the entire series of observations (less than 1 g/dm^3) [2].

It should be noted that according to DSTU 2730:2015 [3, p. 4, 7] in the presence of carbonate ions in all waters, ordinary soda is hypothetically present. But Na_2CO_3 is not always present, so it is not in the sets of hypothetical salts located in front of table 3.

Taking into account formula (1) for different subtypes of water, the formulas for calculating the amount of toxic salts in chlorine equivalents can be written in the following form:

I – $e(rCl^-) = rCl^-+0,2(rSO_4^{2-})+0,4(rMg^{2+})+5(rHCO_3^-+rCO_3^{2-}-rCa^{2+}-rMg^{2+})$;

IIa, IIIa – $e(rCl^-) = rCl^- + 0,2(rSO_4^{2-}) + 0,4(rHCO_3^- - rCa^{2+}) + 5rCO_3^{2-}$;

IIb, IIIb – $e(rCl^-) = rCl^- + 0,2(rSO_4^{2-} + rHCO_3^- - rCa^{2+}) + 5rCO_3^{2-}$;

IIIc – $e(rCl^-) = rCl^- + 5rCO_3^{2-}$.

Let's comment on the first of these formulas. For subtype I waters, all sulfate ions are toxic, they are completely balanced by the part of sodium ions (table. 3.1). The part of bicarbonate ions, balanced by all magnesium ions, is equivalent to their number. Another part of bicarbonate ions, balanced by part of sodium ions, is combined with carbonate ions (since soda is both common and drinking soda are the most toxic to plants).

It should be noted that in the presence of CO_3^{2-} anions, the determination of the required calculated formula $e(rCl^-)$ should be performed on a reduced number of sodium cations with potassium – ($rNa^++rK^+-rCO_3^{2-}$).

Examples of calculation. The initial data are given in Table. 4, where the concentration of ions has an equivalent expression. The table uses observation data on the Kodima River (rowse 1) and the Sasyk Reservoir (rows 2–6).

1) $rCl^-+rSO_4^{2-}<rNa^+$ – subtype I –
$e(rCl^-) = 1,00+0,2*0,57+0,4*2,50+5*(7,90+0,20–4,99–2,50)=$**5,11**;
2) $rCl^-<rNa^+$; $rCl^-+rSO_4^{2-}\geq rNa^+$; $rHCO_3^-\geq rCa^{2+}$ – subtype IIa –
$e(rCl^-) = 11,50+0,2*4,17+0,4*(3,10–2,99)+5*0,40=$**15,9**;
3) $rCl^-<rNa^+$; $rCl^-+rSO_4^{2-}\geq rNa^+$; $rHCO_3^-<rCa^{2+}$ – subtype IIb –
$e(rCl^-) = 13,50+0,2*(7,62+3,20–4,49)+5*0,40=$**16,8**;
4) $rCl^-\geq rNa^+$; $rCl^-<rNa^++rMg^{2+}$; $rHCO_3^-\geq rCa^{2+}$ – subtype IIIa –

Table 4

Initial data for calculation

№ п/п	rCO_3^{2-}	$rHCO_3^-$	rSO_4^{2-}	rCl^-	rCa^{2+}	rMg^{2+}	rNa^++rK^+	Subtype
1	0,20	7,90	0,57	**1,00**	4,99	2,50	2,17	I
2	0,40	3,10	4,17	**11,50**	2,99	4,00	12,17	IIa
3	0,40	3,20	7,62	**13,50**	4,49	5,00	15,23	IIb
4	0,10	3,50	5,53	16,00	3,49	7,50	**14,13**	IIIa
5	0,00	3,40	9,83	14,50	5,99	10,00	**11,74**	IIIb
6	0,40	2,30	2,00	11,00	5,00	2,00	8,70	IIIc

$e(rCl^-) = 16,00+0,2*5,53+0,4*(3,50–3,49)+5*0,10=$**20,6**;

5) $rCl^-≥rNa^+$; $rCl^-<rNa^++rMg^{2+}$; $rHCO_3^-<rCa^{2+}$ – subtype IIIb –

$e(rCl^-) = 14,50+0,2*(9,83+3,40–5,99)+5*0,00=$**15,9**;

6) $rCl^-≥rNa^++rMg^{2+}$ – subtype IIIc –

$e(rCl^-) = 11,00+5*0,40=$**13,0**.

3. Practical use of the proposed methodology. According to the proposed methodology, an assessment of the possibility of soil salinization was carried out when used for irrigation of the waters of the Dniester, Danube and Sarata rivers, as well as the Sasyk, Kuchurgan and Baraboyske reservoirs.

Table 5

Sum of toxic salts in chlorine equivalents for different water bodies during the warm season

Meaning	Sum of toxic salts in chlorine equivalents $e(rCl^-)$					
	Dniester river (Belyaevka)	Danube river (Vilkovo)	Sasyk reservoir (GNS-2)	Sarata river (Bilolissia village)	Kuchurgan reservoir	Baraboy reservoir
Average	1,68	1,01	16,7	53,1	19,7	2,00
Max.	4,43	1,34	28,9	96,3	43,0	5,00
Min.	0,74	0,70	1,68	15,8	5,44	1,00

Table 5 shows the main statistical characteristics of the indicator of the amount of toxic salts in chlorine equivalents $e(rCl^-)$ for the mentioned water bodies during the warm period of the year. Table 6 contains the criteria for water quality classes for different soils in accordance with DSTU 2730: 2015 in terms of $e(rCl^-)$. Figures 5–8 show the security curves of the indicator $e(rCl^-)$ during the warm period.

When comparing information in Table 5, in Fig. 5–8 and in Table 6 we can draw the following conclusions.

With a probability of 100% of the water of the Dniester and Danube rivers belong to the irrigation waters of class I. Use for irrigation of these waters will not lead to salinization of all types of soils, since the maximum values of $e(rCl^-)$ are significantly lower than 10 mg-eq/dm³ (Table 6).

The range of values of the indicator $e(rCl^-)$ for the waters of the Danube is 0.70–1.34 mg-eq/dm³, which is lower than all the water bodies under consideration. Other

Assessment of irrigation water quality by hazard of irrigation salinization of soil (DSTU 2730:2015)

Concentration of toxic ions in chloride ion equivalents by soil groups according to their granulometric composition in a layer of 0–100 cm, mEq/dm³						Water quality class
Sandy	Sandy loam	Easily loamy	Medium loamy	Hard to loamy	Clayey	
< 30	< 26	< 22	< 18	< 14	< 10	I
30 ÷ 40	26 ÷ 36	22 ÷ 32	18 ÷ 28	14 ÷ 24	10 ÷ 20	II
≥ 40	≥ 36	≥ 32	≥ 28	≥ 24	≥ 20	III
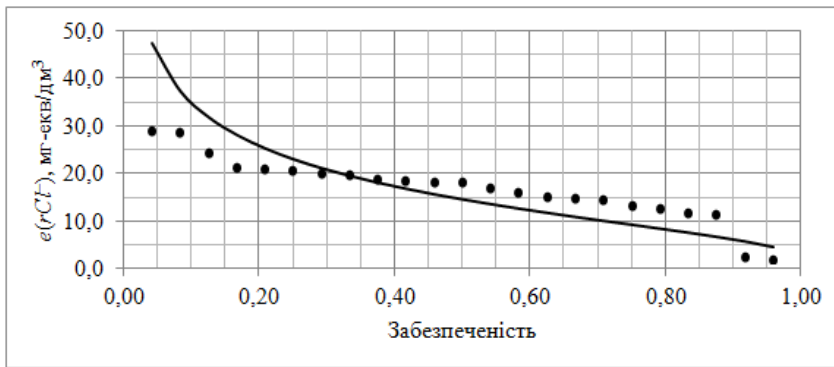
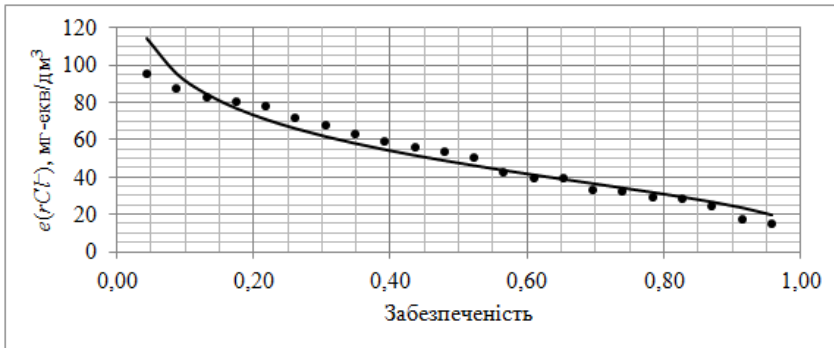*Fig. 5. Distribution of the values of the indicator e(rCl–) in the waters of Sasyk*

Fig. 6. Distribution of values of the indicator e(rCl–) in the waters of the Sarata river

irrigation indicators of the quality of the Danube waters are also very different for the better. The waters of the Danube can be attributed to the standard of irrigation waters.

The waters of Sasyk with a provision of 20–25% can contribute to the salting of sandy and lightly loamy soils (Fig. 5), that is, with a probability of 75–80%, they are safe and belong to class I. With a probability of 75–85% of water, Sasyk belongs to class not lower than II for medium loamy and hard loam soils. For clay soils, the waters of this reservoir belong to class III with a probability of 30–35%.
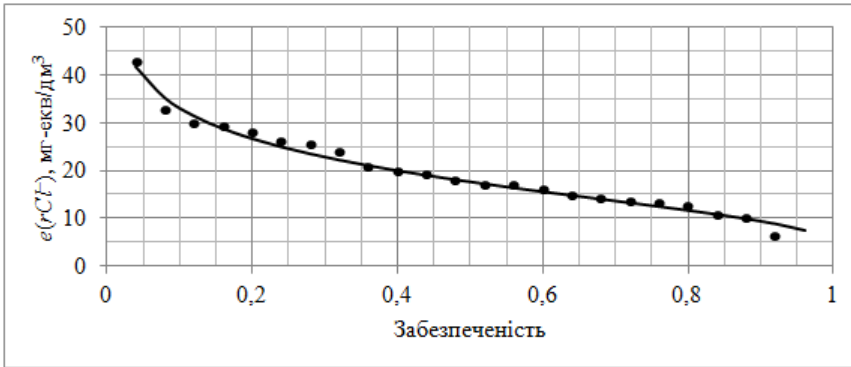
Fig. 7. Distribution of values of the indicator e(rCl⁻) in the waters of the
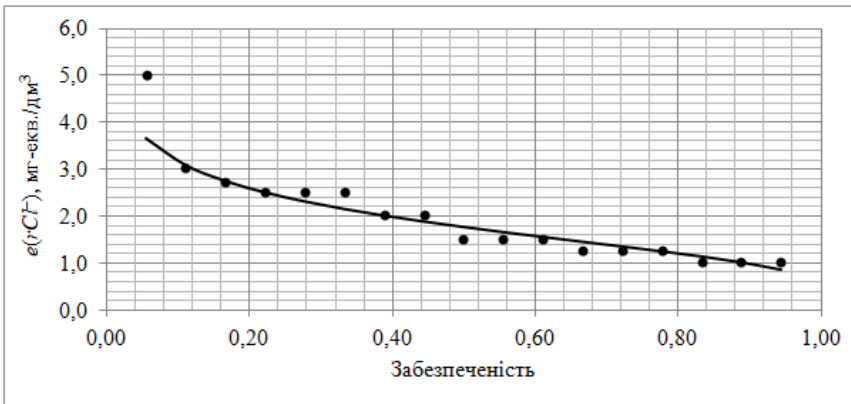*Kuchurgan reservoir*

Fig. 8. Distribution of values of the indicator e(rCl⁻) in the waters
of the Baraboy reservoir

The waters of the Sarata River (Fig. 6) for sandy soils belong to class III with a probability of 55–65%, and for clay soils – 100%. That is, practically these waters are unsuitable for irrigation.

The waters of the Kuchurgan reservoir belong to the class not lower than II for sandy and lightly loamy soils with a probability of 85–90%, for medium loamy and hard loamy soils – 75–80%

The waters of the Baraboy reservoir are completely similar to the Dniester.

Thus, the waters of the Dniester and Danube rivers, as well as the Baraboysk reservoir without the threat of irrigation salinization, are suitable for irrigation of all types of soils. The waters of the Sarata River contribute to the salting of all types of soils. The waters of the Sasitsky and Kuchurgan reservoirs need a careful approach when watering easily permeable soils, when watering hard-to-penetrate soils, the probability of salinization is high.

It should be added that when analyzing the irrigation properties of waters, it is necessary to consider all indicators according to four criteria that are mentioned at the beginning of the article: salt concentration; ion ratio; toxic elements and biogenes. And on the basis of this analysis to conclude about the possibility of using the considered water for irrigation.

Conclusions

1. The proposed detailed typification of irrigation waters makes it possible to simplify the qualitative and quantitative analysis of the chemical composition of salts in water, as well as to simplify the assessment of the threat of irrigation salinization of soils.

2. The waters of the Dniester, Danube and Baraboysky parish rivers belong to class I and are suitable for irrigation of all types of soils without the threat of irrigation salinization.

3. The waters of the Sarata River contribute to the irrigation salting of almost all types of soil.

4. The waters of the Sasitsky and Kuchurgan reservoirs need a careful approach when watering only easily permeable soils, they are not suitable for irrigation of other types of soil.

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