

Agronomic evaluation of irrigation water on the Southern Buh and Kamianska irrigation systems

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RECEIVED 07.06.2021

ACCEPTED 27.10.2021

AVAILABLE ONLINE 28.09.2022

Abstract: The aim of the research was to study the temporal and spatial dynamics of a set of agronomic criteria for irrigation water in the process of transporting it from the Southern Buh River intake site to the lands of the Southern Buh and Kamianska irrigation systems situated in southern Ukraine. Six stationary research sites for monitoring the quality of irrigation water were established along the route of irrigation water transportation. Determination of agronomic criteria for irrigation water quality was carried out in two terms: at the beginning of the irrigation season, in May, and at the end, in September. The content of cations of sodium, magnesium, calcium, and anions of chlorine, sulphates, carbonates, and bicarbonates was determined. In the field, the pH and electrical conductivity of water, the total salt content, and the total amount of dissolved solids were determined. It is determined that waters have an average level of danger from the point of view of salinisation of soils. This fact leads to a decrease in yield of sensitive to salinity crops (corn, alfalfa and most vegetables). The high content of sodium cations along with the low content of calcium and magnesium cations indicates the danger of degradation of the physical properties of the southern chernozems and the need to use the meliorants containing calcium. There is a high probability of toxic effects on crops caused by sodium cations. At the same time, it is stated that there is no negative effect of chlorine anions on plants.

Keywords: bicarbonate, chlorine anions, electrical conductivity, irrigation water, salt content, sodium cations

INTRODUCTION

A large part of Ukraine is located in areas of insufficient and unstable moisture, and therefore the food security of the population and the export potential of the state largely depends on the availability, condition and efficiency of irrigation land use. A factor limiting the development of irrigation in the south of Ukraine is the lack of quality irrigation water.

All criteria for irrigation water quality are grouped into three categories: agronomic, environmental, and management [BORTOLINI *et al.* 2018]. The first category affects crop yields and soil fertility (in particular, the content salts and water-soluble salts composition). The second – determines the impact of irrigation water on human health and environmental quality indicators (content of heavy metals, helminths, *Escherichia coli*, etc.). Finally the third category affects the state of reclamation systems (content of suspended solids, aquatic organisms, manganese, and iron).

Agronomic quality of irrigation water according to FAO (Food and Agriculture Organization of the United Nations), the US Department of Agriculture, and other authors – is determined by several parameters [AYERS, WESTCOT 1994; BORTOLINI *et al.* 2018; USSL 1954; ZAMAN *et al.* 2018]:

- content of water-soluble salts, the high concentration of which leads to salinization of soils, reducing the availability of water and nutrients to plants;
- content of sodium cations, which leads to the degradation of the physical properties of soils, which, in particular, impairs their infiltration properties;
- content of other ions that can accumulate in concentrations toxic to crops, which leads to a decrease in yield and product quality;
- pH value.

The aim of our research was to study a set of agronomic criteria for irrigation water in the process of transporting it from the Southern Buh River to the lands of the Southern Buh and

Kamianska irrigation systems. This assessment allows developing a system of reclamation and agro-technical measures aiming to improve the condition of irrigation water and soil. It may also help to improve the structure of the sown areas, growing more salt-tolerant crops if necessary.

MATERIALS AND METHODS

The Southern Buh Irrigation System (SBIS) and the Kamianska Irrigation System (KIS) located in the south of Ukraine in the Mykolayiv, Veselinovsky, Berezansky, and Ochakivsky districts of the Mykolayiv region, are essentially one water management complex. The source of water for both irrigation systems is the Southern Buh River.

The average perennial flow of the Southern Buh River at the mouth is $115 \text{ m}^3 \cdot \text{s}^{-1}$. The intra-annual flow distribution of the Southern Buh River is characterized by pronounced spring flood (III–IV months), winter (XII–II months) and summer–autumn (V–XI months) low water. The maximum spring flood was observed in 1932 – $5320 \text{ m}^3 \cdot \text{s}^{-1}$, the minimum in 1921 – $76 \text{ m}^3 \cdot \text{s}^{-1}$. The maximum values of summer–autumn flow rates of the Southern Buh River in 1980 were $86 \text{ m}^3 \cdot \text{s}^{-1}$, the minimum value in 1959 was $11 \text{ m}^3 \cdot \text{s}^{-1}$. The maximum winter flow rates of the Southern Buh River in 1981 were $15 \text{ m}^3 \cdot \text{s}^{-1}$, the minimum in 1954 – $12 \text{ m}^3 \cdot \text{s}^{-1}$. All the above observations of runoff were carried out at the Oleksandrivka hydrological station [AFANASYEV *et al.* 2014].

Water is taken from the river near the village of Kovalivka, and then fed to a height of 104.4 m by a pressure water main into a 16.6 km long main canal. It is from this main canal that irrigation is carried out on the lands of SBIS (10.3 thous. ha). Then a part of the water is transferred to the Berezan River basin, and the water is transported by gravity along the riverbed through this system of reservoirs (Stepovske, Danilovske, Katerynivske) to the Nechayanske Reservoir. The water from this reservoir is supplied for irrigation of KIS lands (6.5 thous. ha).

Now the annual use of water from the Southern Buh for irrigation of the lands of the South Buh and Kamianska irrigation systems is 4.7–6.3 mln m^3 . The soil of SBIS and KIS is loamy southern chernozem.

Six stationary research sites for monitoring the quality of irrigation water were laid along the route of irrigation water transportation. The first was on the river Southern Buh in the place of water injection ($47^\circ 15' 04.5'' \text{ N}$, $31^\circ 44' 15.2'' \text{ E}$). The second one was on the main canal ($47^\circ 14' 37.5'' \text{ N}$, $31^\circ 36' 04.9'' \text{ E}$). The third one was on the Stepovske Reservoir ($47^\circ 10' 25.8'' \text{ N}$, $31^\circ 30' 17.3'' \text{ E}$). The fourth was on the Danilovske Reservoir ($47^\circ 00' 21.1'' \text{ N}$, $31^\circ 30' 59.5'' \text{ E}$). The fifth was on the Nechayanske Reservoir ($46^\circ 55' 57.7'' \text{ N}$, $31^\circ 32' 44.5'' \text{ E}$) and the sixth one was on the distribution channel directly near the fields of Mykolayiv National Agrarian University ($46^\circ 56' 11.4'' \text{ N}$, $31^\circ 39' 04.5'' \text{ E}$) – Figure 1.

Determination of agronomic criteria for irrigation water quality was carried out in two terms: in the beginning of the irrigation season, in May, and at the end, in September.

The following laboratory methods were used in the research:

- complexometric determination of calcium and magnesium ions;
- weight method of sulphate ion determination;

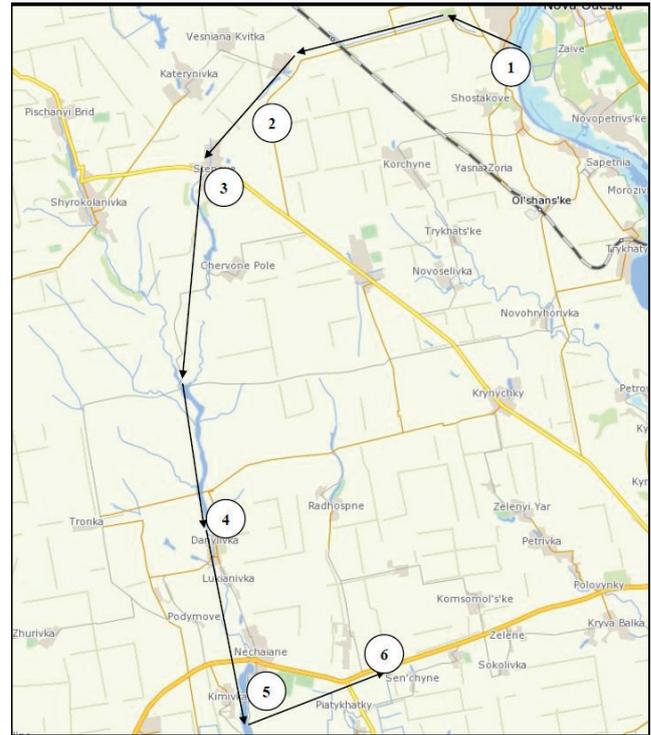


Fig. 1. Scheme of transportation and location of sites for determining the quality of irrigation water; 1 = River Southern Buh, 2 = main canal, 3 = Stepovske Reservoir, 4 = Danilovske Reservoir, 5 = Nechayanske Reservoir, 6 = canal near the fields of Mykolayiv National Agrarian University (MNAU); source: own elaboration

- determination of chlorine ion by argentometric method according to Moore;
- acidimetric determination of carbonate and bicarbonate ions;
- determination of sodium and potassium ions by flame photometry.

In the field, the conductivity of water, the total salt content, and the total amount of dissolved solids were determined by electrochemical methods using a conduct meter EZODO CTS-406. The pH of irrigation water was determined by electrochemical method, using the device EZODO 6011.

Statistical processing of experimental data was performed using MS Excel.

Indicators of agronomic quality of irrigation water were determined by the method of Salinity Laboratory of the US Department of Agriculture (SL USDA) [USSL 1954], as well as more modern methods recommended by FAO [AYERS, WESTCOT 1994], and other authors (HUSSAIN *et al.* [2010], BAUDER *et al.* [2011], KAVURMAC and KARAKUŞ [2020] etc.).

RESULTS AND DISCUSSION

The class of irrigation water is largely provided by water quality in the Southern Buh River. According to hydro chemical observations in the lower reaches of this river, the mineralisation ranges from 260 to 700 $\text{mg} \cdot \text{cm}^{-3}$. The increase in the mineralisation of the water of the Southern Buh is due to the rise in the concentration of all ions of the salt composition, however it is dominated by ions HCO_3^- and Ca^{2+} . The chemical composition and mineralisation of river water is explained by the inflow into

the river and its tributaries of underground bicarbonate waters of calcium-magnesium-sodium composition originating from fractured rocks of the crystalline mass forming the basis of most of the Southern Buh basin. The climatic conditions of the steppe zone are characterised by an annual rainfall of not more than 400 mm and average annual temperatures 3–4°C higher than in the northern (forest-steppe) part of the basin. Caused by increased evaporation and transpiration of water by vegetation, the main part of soil moisture is spent not on the runoff of soil horizons, but on the replenishment of the upper, drier soil layers [KHILCHEVSKYY *et al.* 2009; UKHAN *et al.* 2015].

Soil salinisation is dangerous because the supersaturated with salts aqueous solution has a high osmotic pressure, which prevents the absorption of water and nutrients by the roots, which reduces crop yields significantly. A negative side effect of the high salt concentration presence in the soil solution is the inhibition of photosynthesis.

Based on the SL USDA method [USSL 1954], the assessment of the risk of physical condition deterioration of the soil was performed on the value of electrical conductivity of irrigation water (EC_w in $mS\cdot cm^{-1}$). The most well-known and generally accepted is the USDA Salinity Laboratory Classification [USSL 1954], which determines that the best water with the lowest salinity class (C1) is irrigation water with $EC_w = 0.10\text{--}0.25 mS\cdot cm^{-1}$, middle salinity class (C2) is water with $EC_w = 0.25\text{--}0.75 mS\cdot cm^{-1}$, high class (C3) has irrigation waters with $EC_w = 0.75\text{--}2.25 mS\cdot cm^{-1}$, and very high salinity class (C4) corresponds to the worst waters with $EC_w > 2.25 mS\cdot cm^{-1}$. So, from the point of view of the danger of soil salinisation, irrigation water at the first four observation sites in spring falls into the third class (C3) with an EC_w value of about $0.9\text{--}2.02 mS\cdot cm^{-1}$ (with a salt content of $595\text{--}330 mg\cdot cm^{-3}$). And the last two measurements showed the fourth

class (C4). The September measurement of the electrical conductivity of irrigation water showed almost the same results. It is obvious that the increase in salt content in irrigation water is observed after its transportation through Stepovske, Danilovske and Katerynivske reservoirs (Tab. 1). High evaporation from the surface of reservoirs increases the salt concentration by 2.0–2.5 times, from $450\text{--}500 mg\cdot cm^{-3}$ to $1200\text{--}1300 mg\cdot cm^{-3}$ and EC_w from 0.90 to $2.65 mS\cdot cm^{-1}$. Such values of electrical conductivity and salt content, according to USSL [1954], indicate that irrigation with this water can take place only on soils with high water permeability and constant drainage.

At the same time, more recent FAO [AYERS, WESTCOT 1994] estimates attribute such irrigation water to the average risk of soil salinisation ($EC_w = 0.7\text{--}3.0 mS\cdot cm^{-1}$). Such irrigation water has certain restrictions on use and may lead to reduced yields of individual non-salt-tolerant crops (USSL [1954], AYERS and WESTCOT [1994], GRIEVE *et al.* [2012], ZAMAN *et al.* [2018], NIKOLAOU [2020] etc.).

The degree of tolerance of an agricultural plant to salts when irrigated with mineralised water can be described as a function of the potential decrease in yield (Z , %) of the salt concentration in irrigation water determined by electrical conductivity (EC_w). Two parameters are used – electrical conductivity which triggers the decrease in yield of a particular crop, and the value of “slope” (δ). The latter is the percentage of expected decrease in yield per unit increase in salt content above the threshold value [GRIEVE *et al.* 2012]:

$$Z = \delta(EC_w - EC_{wo}) \quad (1)$$

where: Z = a function of the potential decrease in yield, δ = the percentage of expected decrease in yield per unit increase in salt content above the threshold value, EC_w = electrical conductivity

Table 1. Indicators of irrigation water quality of Southern Buh Irrigation System and Kamianska Irrigation System (May, September)

Parameter	Unit of measurement	Southern Buh River (1)	Main canal (2)	Stepovske Reservoir (3)	Danilovske Reservoir (4)	Nechayanske Reservoir (5)	Canal MNAU (6)
May							
CO_3^{2-}	mg-eq-cm ⁻³	2.0 ±0.2	2.8 ±0.03	2.4 ±0.38	2.1 ±0.1	2.8 ±0.05	3.5 ±0.05
HCO_3^-		4.9 ±0	6.0 ±0.05	5.3 ±0.3	4.6 ±0.7	6.0 ±0.22	8.0 ±0.2
Cl^-		0.1 ±0.06	0.1 ±0.01	0.1 ±0.01	0.3 ±0.03	0.4 ±0	0.5 ±0.01
SO_4^{2-}		0	0	0	0	0	0
Mg^{2+}		0	0.4 ±0.02	0.3 ±0	0.7 ±0.2	0.9 ±0.06	0.8 ±0.05
Ca^{2+}		0.6 ±0.15	0.5 ±0.05	0.5 ±0.03	0.5 ±0	0.3 ±0	0.4 ±0.03
Na^+		1.3 ±0	1.3 ±0	1.4 ±0	3.5 ±0	5.4 ±0	4.9 ±0
K^+		0.2 ±0	0.2 ±0	0.3 ±0	0.4 ±0	0.6 ±0	0.6 ±0
pH	–	8.6	8.0	7.7	8.5	8.4	8.4
EC_w	mS·cm ⁻¹	0.90 ±0	0.94 ±0	0.92 ±0	2.02 ±0	2.65 ±0	2.54 ±0
Mineralisation	mg·cm ⁻³	595.0 ±0	621.0 ±0	603.0 ±0	1330.0 ±0	1740.0 ±0	1670.0 ±0
SAR	–	2.3	1.9	2.2	4.7	7.1	6.5
RSCI	mg-eq-cm ⁻³	6.0	7.9	6.6	5.5	7.6	10.9
General alkalinity		6.9	8.8	7.7	6.7	8.8	11.5
The content of toxic cations (Na+K)	%	69.8	61.2	68.5	77.7	83.7	83.1

cont. Tab. 1

Parameter	Unit of measurement	Southern Buh River (1)	Main canal (2)	Stepovske Reservoir (3)	Danilovske Reservoir (4)	Nechayanske Reservoir (5)	Canal MNAU (6)
September							
CO ₃ ²⁻	mg-eq·cm ⁻³	0	0	0	0	0	0
HCO ₃ ⁻		3.8 ±0.35	4.0 ±0.06	4.2 ±0.13	4.4 ±0.2	4.6 ±0.2	3.6 ±0
Cl ⁻		0.4 ±0.01	0.4 ±0	0.5 ±0.02	1.1 ±0.05	1.7 ±0.03	0.9 ±0.04
SO ₄ ²⁻		2.7 ±0.03	2.6 ±0.1	1.6 ±0.04	2.4 ±0.2	3.3 ±0.02	1.6 ±0.05
Mg ²⁺		0.4 ±0.02	0.4 ±0.02	0.1 ±0.02	0.1 ±0.01	0	0.1 ±0.05
Ca ²⁺		0.2 ±0	0.2 ±0	0.3 ±0.18	0.3 ±0.03	0.3 ±0	0.2 ±0
Na ⁺		1.7 ±0	1.7 ±0	2.2 ±0	4.4 ±0	6.6 ±0	5.0 ±0
K ⁺		0.2 ±0	0.2 ±0	0.3 ±0	0.5 ±0	0.6 ±0	0.5 ±0
pH	–	8.2	8.3	8.2	8.2	8.2	8.2
EC _w	mS·cm ⁻¹	0.96 ±0	0.95 ±0	1.07 ±0	1.86 ±0	2.65 ±0	2.14 ±0
Mineralisation	mg·cm ⁻³	632.0 ±0	623.0 ±0	707.0 ±0	1228.5 ±0	1750.0 ±0	1410.0 ±0
SAR	–	3.2	3.2	4.8	9.8	15.8	12.5
RSCI	mg-eq·cm ⁻³	3.2	3.6	3.8	4.1	4.3	3.6
General alkalinity		3.8	4.0	4.2	4.4	4.6	3.6
The content of toxic cations (Na+K)	%	76.6	76.6	85.6	92.5	95.4	94.5

Explanations: MNAU = Mykolayiv National Agrarian University, EC_w = electrical conductivity of irrigation water, SAR = sodium adsorption ratio, RSCI = residual sodium carbonate index.

Source: own study.

of irrigation water, EC_{wo} = the threshold value of electrical conductivity from which begins the decrease in yield of a particular crop. Obviously, if EC_w < EC_{wo}, then Z = 0.

Calculations for equation (1) provided for the main crops of SBIS and KIS (Tab. 2) showed that onions and carrots irrigated with water from experimental sites 4–6 are most sensitive to salinisation which consequently leads to yield losses of approximately 12–20%. For medium salt tolerance crops (corn, alfalfa, cabbage, tomatoes) yield losses will be 2–12% whereas for salt

tolerant crops (soybeans, winter wheat, and table beets) there will be no yield losses.

Deterioration of physical properties of soil during watering is associated with the presence of sodium cations in the soil-absorbing complex. Irrigation of soils by medium and heavy particle size distribution can lead to deterioration of soil structure, reduction of water permeability, increased density, etc. In such soils, the water balance of the soil is modified, in particular, the surface runoff increases, which negatively affects the provision of root systems of plants with water.

Table 2. Assessment of salt resistance of major crops of Southern Buh Irrigation System and Kamianska Irrigation System

Crop	EC _{wo} (mS·cm ⁻¹) [GRIEVE <i>et al.</i> 2012]	δ (%) [GRIEVE <i>et al.</i> 2012]	Reduced yield percentage at different values of EC				Salt resistance rating [GRIEVE <i>et al.</i> 2012]
			1.5	2.0	2.5	3.0	
			mS·cm ⁻¹				
Corn (grain)	1.7	12.0	0	3.6	9.6	15.6	MS
Soybean	5.0	20.0	0	0	0	0	MT
Winter wheat	6.0	7.1	0	0	0	0	MT
Alfalfa	2.0	7.3	0	0	3.6	7.3	MS
Tomato	2.5	9.9	0	0	0	5.0	MS
Cabbage	1.8	9.7	0	1.9	6.8	11.6	MS
Onion	1.2	16.0	4.8	12.8	20.8	28.8	S
Beet	4.0	9.0	0	0	0	0	MT
Carrot	1.0	14.0	7.0	14.0	21.0	28.0	S

Explanations: EC_{wo} = threshold value of electrical conductivity, EC = electrical conductivity, δ = the percentage of expected decrease in yield per unit increase in salt content above the EC_{wo}, S = sensitive, MS = moderately sensitive, MT = moderately tolerant, T = tolerant.

Source: own study.

To assess the risk of deterioration of the physical soil condition, according to USSL [1954], AYERS and WESTCOT [1994], ZAMAN *et al.* [2018] etc., the most informative is the SAR (sodium adsorption ratio), which is calculated as follows:

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}} \quad (2)$$

where: Na , Ca , Mg = content of sodium, calcium and magnesium cations in irrigation water ($\text{mg}\cdot\text{eq}\cdot\text{cm}^{-3}$).

Studies have shown (Tab. 1) that from the place of injection of water from the river into the water supply to the distribution channel, from which the fields of MNAU are irrigated, the sodium content increases from $1.3\text{--}1.7 \text{ mg}\cdot\text{eq}\cdot\text{cm}^{-3}$ to $5.4\text{--}6.6 \text{ mg}\cdot\text{eq}\cdot\text{cm}^{-3}$. Whereas the amount of toxic cations, where sodium ions predominate, rises from 70 to 84% in May, and from 77 to 95% in September. Against this background, SAR levels increase from 1.9 to 7.1 (May) and from 3.2 to 15.8 (September). It should be noted that the content of sodium cations and the value of SAR rises almost fourfold both in May and September in the process of transporting water from the Southern Buh River to the Nechayanske Reservoir (Tab. 1).

According to the widely used methodology of the US Department of Agriculture's Salinity Laboratory [USSL 1954], $SAR < 10$ is a low level of sodium cations in irrigation water (class S1), which does not cause significant deterioration of water-physical properties. The value of $SAR = 10\text{--}18$ (class S2) refers to the average level of sodium cations in irrigation water (Fig. 2). Loamy and clayey soils with high absorptive capacity and lack of the required amount of carbonates in the soil are at risk of rapid deterioration of physical and water-physical properties when irrigated with such water. Such waters can be used for irrigation of either sandy soils with low cation absorption capacity or well-permeable organic soils. In other cases, a number of agronomic measures and chemical reclamation with gypsum are needed, which will counteract the deterioration of the physical and water-physical condition of the soil [BALYUK *et al.* 2009].

At the same time, there are more comprehensive estimates of SAR values. In particular, FAO experts and other authors [AYERS, WESTCOT 1994; ZAMAN *et al.* 2018] assess the risk of degradation of physical properties of soils including the rate of water infiltration into the soil, depending on the salt content, which, in turn, is a function of electrical conductivity [AYERS, WESTCOT 1994]. In such estimates, the risk of degradation of physical properties of soils and reduction of soil infiltration capacity during watering and precipitation will be the greatest in conditions of relatively low total salt content in water and small values of EC_w accordingly. Conversely, when irrigated with highly mineralised irrigation water, the risk of deterioration of the physical properties of soils will be minimal even at high SAR values. From these positions, irrigation water with SAR values = $1.9\text{--}4.7$ and $EC_w = 0.9\text{--}2.0 \text{ mS}\cdot\text{cm}^{-1}$ (indicators from research sites No. 1–4 in May) and SAR = $3.2\text{--}4.8$ and $EC_w = 0.9\text{--}1.1 \text{ mS}\cdot\text{cm}^{-1}$ (indicators from research sites No. 1–3 in September) has medium risks of degradation of physical properties of soil [AYERS, WESTCOT 1994]. The increase of sodium cations content and SAR values up to $6.5\text{--}7.1$ at the experimental sites No. 5 and No. 6 during measurements in May, which is accompanied by a simultaneous increase of EC_w to

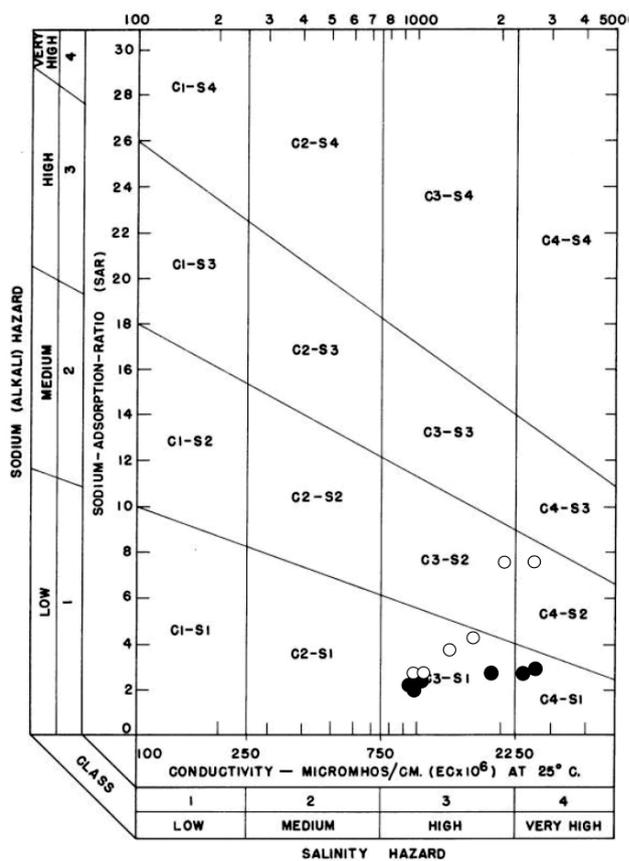


Fig. 2. Scheme of transportation and location of sites for determining the quality of irrigation water; source: own study

$2.5\text{--}2.6 \text{ mS}\cdot\text{cm}^{-1}$. Such data allows us to state the complete absence of danger of deterioration of physical and water-physical properties according to the FAO method [AYERS, WESTCOT 1994]. September's measurements show that at $SAR = 9.8\text{--}15.8$ and $EC_w = 1.9\text{--}2.7 \text{ mS}\cdot\text{cm}^{-1}$ (indicators from experimental sites No. 4–6) there is an average level of risk of degradation of physical and water-physical properties.

In most cases, there is a multiple increase in sodium cations and SAR values during water transportation, which has medium risks in terms of negative impact on the physical and water-physical properties of loamy southern chernozem. This growth is accompanied by a simultaneous increase in the total mineralisation and electrical conductivity of water, which partially eliminates the dangerous effect of sodium cations. Therefore, given the low content of carbonates in the soil, in most cases irrigation on SBIS and KIS will lead to a certain deterioration of the physical properties of soils, which should be offset by chemical reclamation of chernozem with gypsum and other compounds containing calcium [BALYUK *et al.* 2009].

The problem of toxicity of individual ions differs from the problem of salinisation and physical degradation of soils. This process takes place inside the plant, when ions are absorbed from the soil and accumulate in toxic amounts in the stems and leaves, which degrades product quality and reduces crop yields.

Sodium cations and chlorine anions, as well as some metal and semi-metal ions (B, Fe, Cu, Zn, Mn, Cr) are generally considered toxic ions in irrigation water (AYERS and WESTCOT [1994], ZAMAN *et al.* [2018] etc.). But it should be noted that the above chemical elements are not contained in significant concentrations

in irrigation water from the Southern Buh. According to KHILCHEVSKYY *et al.* [2009] and UKHAN *et al.* [2015], in the water of the lower course of this river the iron content varies within 0.14–0.25 mg·cm⁻³ (max. allowable 5.0 mg·cm⁻³), copper – 0.004–0.007 mg·cm⁻³ (max. allowable 0.2 mg·cm⁻³), zinc – 0.007–0.009 mg·cm⁻³ (max. allowable 2.0 mg·cm⁻³), manganese – 0.01–0.04 mg·cm⁻³ (max. allowable 0.2 mg·cm⁻³), chromium – 0.006–0.009 mg·cm⁻³ (max. allowable 0.1 mg·cm⁻³).

The content of sodium cations does not exceed 2.0 mg·eq·cm⁻³ in the water of the Southern Buh [KHILCHEVSKYY *et al.* 2009]. This fact is also confirmed by our research. In the process of transportation after the passage of water through a number of reservoirs, the sodium content increases several times, reaching values of 5.4–6.6 mg·eq·cm⁻³. The main reason for this phenomenon is temperature changes of irrigation water. In the presence of excess carbonates during the evaporation of the solution, takes place the process of formation of insoluble calcium carbonates (CaCO₃) and magnesium carbonates (MgCO₃), which precipitate from the solution. At the same time, increasing water temperature in reservoirs, especially in summer, increases the solubility of salts such as Na₂SO₄ and NaCl. As a result, the relative and absolute content of sodium cations increases, and the SAR value increases to toxic values for plants [AYERS, WESTCOT 1994]. According to studies of water quality indicators, no toxic effects of sodium were observed in May during irrigation from experimental plots No. 1–3 (SAR < 3). Irrigation waters from sites No. 4–6 are of medium danger [AYERS, WESTCOT 1994]. September studies showed that the average risk of toxic effects of sodium cations occurs when watering from experimental sites No. 1–3 (SAR = 3–9), and a high risk of toxic effects of sodium cations when watering from experimental sites No. 4–6 (SAR > 9). In the case of irrigation by sprinkling, the content of sodium cations exceeds 3.0 mg·eq·cm⁻³ for all observation sites, which is dangerous for all agricultural plants [AYERS, WESTCOT 1994].

Chlorides are almost always found in water used for irrigation. But the initial content of chlorine anions in the Southern Buh River and even a small increase in the content of this ion during transportation does not exceed the threshold value of 3.0 mg·eq·cm⁻³. This indicates the absence of a negative effect of this anion on crop yields [AYERS, WESTCOT 1994; NIKOLAOU *et al.* 2020].

Agronomic assessment of irrigation water quality using the methods of SL USDA and FAO, and other authors (AYERS, WESTCOT [1994]; GRIEVE *et al.* [2012]; ZAMAN *et al.* [2018]; NIKOLAOU [2020] etc.) also shows that it is necessary to assess the content of nitrates, bicarbonates and pH. The presence of these chemical elements and high pH values negatively affect the soil conditions of plant nutrition. At the same time, hydro chemical studies of nitrate content in the waters of the Southern Buh River showed [KHILCHEVSKYY *et al.* 2009; UKHAN *et al.* 2015] that their average amount in the place of irrigation water intake, i.e. in the lower reaches of the river, is 0.010–0.015 mg·eq·cm⁻³, which is two orders of magnitude less than the normalised value of 1.5 mg·eq·cm⁻³ [AYERS, WESTCOT 1994], and therefore this indicator was not taken into account for the analysis of irrigation water quality in SBIS and KIS.

The bicarbonate content is an important indicator of irrigation water quality. Its excess, as mentioned above, leads to the formation of insoluble calcium and magnesium carbonates, and to relative sodium cations content increase in the water,

which leads to an increase of this cation toxic effect on plants, especially in hot days, and the spread of physical soil degradation.

The water of the Southern Buh contains 5.0 mg·eq·cm⁻³ of bicarbonate, so it dominates among all anions. The high content of bicarbonates is explained by the processes of chemical weathering as a result of dissolution of carbonate rocks such as limestone, marl, dolomite. In addition, a sufficient amount of precipitation in the upper and middle parts of the Southern Buh basin creates periodic leaching of soils in this area, which stimulates the ingress of HCO₃⁻ anions into groundwater and the formation of specific ionic runoff of the river [KHILCHEVSKYY *et al.* 2009; UKHAN *et al.* 2015].

The May determination of irrigation water quality indicators showed that the HCO₃⁻ bicarbonate content ranges from 4.6 to 8.0 mg·eq·cm⁻³, which in some cases (experimental sites No. 2, 3, 5 and 6) indicates the average risk of adverse effects of this anion on the soil solution and the plants. The September determination of bicarbonate at all observation sites showed the absence of any danger of leaching of the soil solution: the content of HCO₃⁻ was less than 5.0 mg·eq·cm⁻³ (Tab. 1).

The residual sodium carbonate index (RSCI) is a more comprehensive indicator of the impact of carbonates and bicarbonates on irrigation water quality. It evaluates the combined effect of these anions and cations of magnesium and calcium on the risk of toxic increase of sodium cations. This indicator is widely used in assessing the quality of irrigation water in countries with arid and semi-arid climates (HUSSAIN *et al.* [2010], KAVURMAC and KARAKUŞ [2020]; NIKOLAOU *et al.* [2020]; SINGH *et al.* [2020] etc.). It is calculated as:

$$RSCI = (HCO_3 + CO_3) - (Ca + Mg) \quad (3)$$

where: RSCI = residual sodium carbonate index, HCO₃ and CO₃ = content of hydrogen carbonate and carbonate anions, mg·eq·cm⁻³, Ca and Mg = content of calcium and magnesium cations, mg·eq·cm⁻³.

Most authors believe that an RSCI value of 2.5–5.0 mg·eq·cm⁻³ is acceptable for safe irrigation. In this case, according to the May estimates of water quality in SBIS and KIS at all observation sites RSCI exceeds 5.0 mg·eq·cm⁻³, and therefore the water is not very suitable for irrigation. And the measurement of this indicator in September shows the average level of danger of a possible increase in the toxic effects of sodium cations on plants and soil.

The value of the hydrogen index (pH) in surface waters is usually formed within the carbonate-calcium system in the form of several components – calcium cations, carbonate and bicarbonate ions and carbon dioxide. This balance state of the system is determined by the temperature regime of water bodies, on which the solubility of CO₂ and the intensity of hydro biological processes depend. The pH value in surface waters increases with decreasing CO₂ content due to increasing water temperature or intensive photosynthesis of aquatic organisms, in particular blue-green algae, and decreases with increasing CO₂ content. In our case (Tab. 1), the pH value is relatively stable both on the transport route and during the irrigation season, due to the presence of a large number of bicarbonate ions, which compensate for the reduction of CO₂ when heating water. The formation of carbonic acid, which determines the value of the hydrogen index, in this case is almost independent of the

concentration of carbon dioxide, and therefore the pH value does not change. Thus, the range of 6.5–8.6, which was observed in water quality studies, according to regulatory values and data of other authors [HUSSAIN *et al.* 2010; KAVURMAK, KARAKUŞ 2020; NIKOLAOU *et al.* 2020; SIMSEK, GUNDUZ 2007; SINGH *et al.* 2020], can be defined as safe for most crops.

CONCLUSIONS

1. From the point of view of salinisation of soils, waters have an average level of danger ($EC_w = 0.7\text{--}3.0 \text{ mS}\cdot\text{cm}^{-1}$). Such irrigation water has certain limitations in use. In particular, for the most sensitive to salinity crops (onions and carrots) watering with this water will lead to a loss of yield of about 12–20%. For the crops of medium salt resistance (corn, alfalfa, cabbage, tomatoes) yield losses will be 2–12%, and for salt-tolerant crops (soybeans, winter wheat, table beets) there will be no yield losses.
2. The content of sodium cations in irrigation water ($1.3\text{--}6.6 \text{ mg}\cdot\text{eq}\cdot\text{cm}^{-3}$) and the SAR value (1.9–15.8) indicate average risks of physical degradation of southern chernozem. Due to the low content of carbonates in the soil, land users should perform chemical reclamation of chernozem with gypsum and other compounds that contain calcium.
3. According to the existing criteria, the risk of toxic effects of sodium cations on agricultural plants will be relatively small during surface watering. However, September studies showed that irrigation from the Nechayanske Reservoir on the lands of the Kamianska Irrigation System has a certain risk of toxic effects of sodium cations ($SAR > 9$).
4. The low content of chlorine anions ($<3 \text{ mg}\cdot\text{eq}\cdot\text{cm}^{-3}$) in irrigation water will not lead to its toxic effects on plants.
5. An important criterion for assessing the potential danger of the formation of excess sodium cations, especially in hot weather, is the content of HCO_3^- hydro carbonate in irrigation water. Determination of the content of this anion ($4.6\text{--}8.0 \text{ mg}\cdot\text{eq}\cdot\text{cm}^{-3}$) showed the average danger probability. However, comprehensive RSCI indicator usage indicates the danger of irrigation with such water in spring and probably during the summer ($RSCI > 5 \text{ mg}\cdot\text{eq}\cdot\text{cm}^{-3}$). At the same time, the September measurements show an average level of danger of a probable increase in the toxic effects of sodium cations on plants and soil.
6. The pH values of irrigation water most often fit the range of values acceptable for most crops (6.5–8.6).

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