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INDUSTRIAL PROBLEMS OF THE STUDY OF ARID TERRITORIES

Salinization of Soils in the Don Valley under Conditions of Terminated Irrigation

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Abstract—This article presents a study for the identification of the current salt state of the soils of the General Irrigation System built near the Tsimlyansk reservoir in 1959 in the dry-steppe zone of Volgograd oblast in the Don Valley. The system is currently in a 30-year irrigation shutdown period. In the interpolation study, soil-salinity maps that cover different soil depths were constructed. They are based on field surveys and water-extract data (1 : 5) from soil samples taken in 2020. Water-extract data obtained at the Volgograd Hydrogeological and Land Reclamation Expedition in 2018 were also used. The key area of study was located on the second floodplain left-bank terrace of the Don River and included a territory in which a high groundwater level (1.5–3 m) with strong mineralization (3–10 g/L) formed by the beginning of the 1990s during a long period of irrigation. This led to the formation of a meadow solonchak and secondary saline soils with a high degree of salinity, which prompted us to map the salinity of soils in this area and to determine the changes over the past period. Analysis of the soil-salinity maps made it possible to assess the current salt state of soils located on various relief elements of the second terrace of the Don River and to compare the current salt state of soils with the period of the late 1980s–early 1990s, which showed a gradual desalinization of previously saline areas and the development of alkalization of the upper soil horizons. The desalinization was caused by the cessation of irrigation, and alkalization was caused by the location of the general system in the solonetz zone, the long period of irrigation from 1960 to 1992, and irrigation from the Tsimlyansk reservoir with water with a high sodium concentration. Salinity maps showing the depth of the salt horizon provide information necessary for the development and selection of optimal reclamation measures to restore the soil fertility. Preliminary recommendations for the solution of this problem upon the resumption of can include quality control of the irrigation water, the use of periodic (once every several years) water-charging spring washing of the 0- to 70-cm layer to push accumulated salts out of the aeration zone, gypsum to ensure the displacement of exchangeable sodium, suppression of the alkalinity and the removal of water-soluble sodium to the underlying horizons beyond the root layer, the use of drip irrigation, and an increase in the share of perennial legumes and cereals in the structure of sown areas. The article also shows that the spectral indices given in the literature cannot be used to determine the soil salinity from space information in relation to the selected study area. This was confirmed with multiple regression analysis, in which the values of the spectral indices in four image channels from the Sentinel-2 satellite and the salinity values of different soil horizons at the sampling points obtained as a result of field and laboratory work were used as features. According to the results of regression analysis, no significant relationship between the spectral indices and salinity values was revealed in any soil horizon. The resulting correlation coefficients were less than 0.5, and, hence, the relationship was very low.

Keywords: soil salinization, irrigation system, interpolation method, soil mapping
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INTRODUCTION

In the middle of the 20th century, large irrigation systems were built in Russia, which ensured the food security of the country. The most active construction was carried out in the 1950–60s, and the developed areas of irrigated land reached their peak by the mid-1980s. However, the economic crisis of the 1990s led to a reduction in their area and changes in the management of irrigation and drainage systems. Many irrigated lands were abandoned to the state of perennial deposits, and the rest were transferred to rainfed use. In some areas, irrigation was resumed only after a long period of abandonment. Such cardinal changes in the use of irrigated lands could not but affect the condition of the soils.

At present, the state's efforts are aimed at the reconstruction of irrigation systems in order to restore irrigation and to reclaim irrigated lands. To achieve this, it is essential to assess the current salt state of soils with allowance for the duration of the irrigation period and interruptions in irrigation. The study of irrigated soils makes it possible to select and carry out the necessary agroreclamation measures to restore their fertility.

The General Irrigation System (GIS) is one of the first large state systems in southern Volgograd oblast. It was built on the basis of the Tsimlyansk reservoir in 1959; its area was 12439 ha (Irrigation systems of Russia, 2013). In the early 1990s, due to the economic crisis in the country, the irrigation and cultivation of land on the IS ceased, and the cultivation of agricultural crops resumed only in 2000.

According to the Volgograd Hydrogeological and Land Reclamation Expedition (VHLRE), the area of GIS agricultural lands amounted to 6895 ha in 2001 and 4870 ha since 2015, i.e., it decreased by 1.4 times. The land is currently being used entirely for rainfed agriculture with the prospect of resuming irrigation. The total area of agricultural land has not changed since 2015 and remains 4870 ha. Winter cereals and industrial (mustard) crops are cultivated, and many fallow lands are preserved.

In the latest literature, a large number of articles describe the experience of irrigation and its consequences in various regions of the globe, primarily on the basis of satellite information. Research on soil salinity is carried out in the Middle East (Allbed et al., 2014), North Africa (Hihi et al., 2019), Turkey (Gorji et al., 2017), China (Jiang and Shu, 2018; Wang et al., 2019; Chi et al., 2019; Ren et al., 2019), and Russia (Komissarov et al., 2019; Gorokhova et al., 2018–2020).

Combinations of different satellite imagery channels and calculated, empirically derived indices are often used to identify solonchaks, as well as saline and nonsaline soils (Douaoui et al., 2006; Bouaziz et al., 2011; Abbas et al., 2013; Allbed et al., 2014; Hihi et al., 2019). However, in our opinion, there is no strictly defined combination of channels or universal indices to assess the state of soil salinity. In each specific case, individually selected approaches should be used.

The purpose of this research is (a) to evaluate the potential for the use of spectral indices of soil salinity from literary sources based on space images in relation to the territory of the GIS and (b) to map the current salinity of the GIS soils after a 30-year period of cessation of irrigation.

MATERIALS AND METHODS

The object of research was the soil of the GIS, which is located in the dry steppe zone of Volgograd oblast. The irrigation system is located mostly on the second floodplain left-bank terrace of the Don River and partly on the northwestern slope of the Ergeni Upland. The key research area occupies part of the terrace of the Don River (Fig. 1).

The second Upper-Quaternary, above-floodplain terrace of the Don developed in separate sections, the width of which is 1.5–3.0 km, and the height above the river edge does not exceed 60 m. It is composed of alluvial sands with interlayers and lenses of loams and clays. The first terrace above the floodplain is hidden under the waters of the Tsimlyansk Reservoir (Kretinin, 2011).

In the 1960s, the groundwater level (GWL) in the Don Valley fluctuated from a few meters to 10 m. According to the VHLRE, the GWL on the GIS had increased by the 1990s, reaching 1.5–3 m in the Don Valley and 3–5 m on the slope of Ergeni. The groundwater mineralization increased from 1–3 to 3–10 g/L. The chemical composition of the water varied, with a predominance of sulfates and chlorides in various combinations. At present, the GWL over the entire area of the GIS is >5 m. There were no changes in the chemical composition of the water during the irrigation period.

The entire GIS territory is characterized by a complexity of the soil cover, which is represented by chestnutm zonal, meadow- and meadow–chestnut soils of microdepressions with spots of solonetzes.

Some of the soils of the Don Valley have undergone significant changes during the irrigation period. The high level (1.5–3 m) and strong mineralization (3–10 g/L) of groundwater led in the late 1980s and early 1990s led to the formation of a solonchak with an area of several hundred square meters surrounded by secondary saline soils with a high degree of salinity. In 1992, irrigation at the GIS was suspended, and the land has been used entirely for rainfed agriculture since 2000.

In August–September 2020, employees of the Dokuchaev Soil Institute conducted field research at the GIS within the boundaries of the second terrace of the Don River. The key area covered the slightly dissected slope of the terrace, which included the main slope and the gentle sides of a wide hollow directed towards the reservoir (points G-25-20 to G-21-20, absolute heights of 50.5–51.5 m), the space above the main slope and the sides of a shallow hollow (points G-3-20 to G-13-20, absolute height of 54.0–55.5 m), a former solonchak located closest to the Tsimlyansk reservoir (points G-26-20 to G-27-20, absolute height of 46.0–46.5 m). A total of 16 sections and excavations were laid and described, and 152 soil samples were analyzed for soil salinity via water extraction (1 : 5).

In addition, the VHLRE data for 2018 were used. These are the results of the water extraction of 17 soil sections located on a slightly dissected slope of the terrace (points G-2-18 - G-18-18, absolute height of 50–60 m).

The construction of interpolation maps of soil salinity was carried out in the Surfer-13 software package with the “kriging” interpolation method; the ground coordinates and the anisotropy of the location of points along the horizontal were taken into account. Kriging is a geostatistical, spatial interpolation

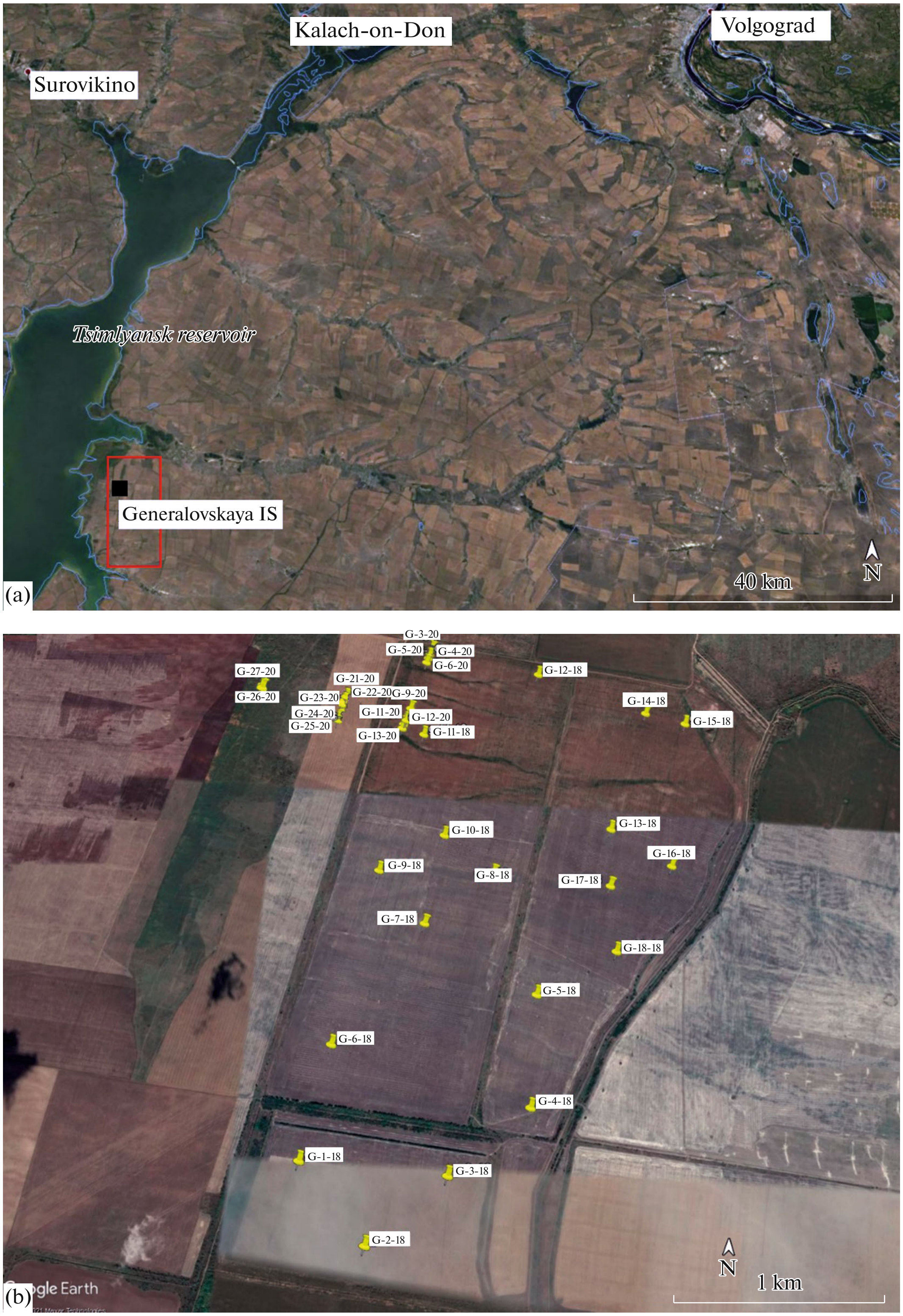

Fig. 1. (a) The location of the GIS and the key site of field research (black square), (b) the field sampling points at the key GIS site in 2020 and 2018 as marked on the satellite image of the Google.Earth portal (12/27/2019).

Table 1. Regression and correlation coefficients calculated from the spectral indices of soil salinity from the literature sources and salinity values of different soil horizons at sampling points in the key area of the GIS

Index salinity soil	Source and study area	Regression coefficients for different soil horizons, cm				
		0–30	30–50	50–100	100–150	150–200
$SI = \sqrt{G^2 + R^2}$	Douaoui et al. (2006), Algiers	2.10×10^{-6}	2.58×10^{-6}	5.57E-06	4.65×10^{-5}	7.87×10^{-5}
$SI = \sqrt{GR}$	Bouaziz et al. (2011), Northeast Brazil	1.46×10^{-5}	8.71×10^{-6}	2.70×10^{-5}	1.01×10^{-5}	7.18×10^{-6}
$SI = \sqrt{R^2 + G^2 + NIR^2}$	Abbas et al. (2013), Pakistan	1.52×10^{-5}	1.44×10^{-6}	9.34×10^{-6}	6.79×10^{-5}	0.000104972
$SI = \sqrt{R^2 + G^2 + NIR^2}$		0.534623887	0.44312476	2.041167194	2.04369157	1.884813686
$SI = \frac{B - R}{B + R}$		0.086471288	0.08726639	0.000714968	0.372209169	0.19446472
$SI = \frac{GR}{B}$		2.66×10^{-5}	1.48×10^{-5}	3.70×10^{-5}	3.93×10^{-6}	1.92×10^{-5}
$SI = \sqrt{BR}$		2.57×10^{-5}	2.71×10^{-5}	2.41×10^{-6}	2.79×10^{-6}	2.47×10^{-5}
Correlation coefficient		0.26	0.49	0.42	0.25	0.22

B, blue (0.4–0.5 μm); *G*, green (0.5–0.6 μm), *R*, red (0.6–0.7 μm); *NIR*, near-infrared (0.7–0.95 μm) satellite imagery channels.

method based on linear regression. Model variograms were built to create maps with a similar method, and they were used to estimate the spatial correlation of the values.

RESULTS AND DISCUSSION

The potential for the use of spectral indices of the soil salinity from literary sources, which were calculated from satellite images in relation to the study area, was first determined in order to assess the salinity of GIS soils. A multiple regression analysis was carried out for this purpose. The values of the spectral indices in four channels of the image from the Sentinel-2 satellite dated March 28, 2020 (Copernicus Open Access Hub, 2020), and the salinity values of different soil horizons at sampling points obtained from field and laboratory work were used as features. It was assumed that the spectral indices with the highest correlation coefficients can be further used to calculate the soil salinity for the GIS territory. However, according to the results of regression analysis, no significant relationship was found between the spectral indices and salinity values in any soil horizon. The obtained correlation coefficients were less than 0.5, and, consequently, the relationship turned out to be very low (Table 1).

Thus, the calculations confirmed our assumptions that there are no universal indices to determine the soil salinity and that individually selected methods should be used in each specific case for the assessment of soil salinity in different areas.

Since it was established based on field studies at sampling points in the key area of the GIS that the salinization in the soils is sufficiently deep, we chose the interpolation method to build the maps. The degree and type of chemistry of soil salinization were determined by the amount of toxic salts (Stox, %) according to the method of Bazilevich and Pankova (1972; *Zasolennye pochvy*..., 2006). The salinization at the GIS was determined to be chloride-alkaline and chloride-sulfate, chloride, sulfate-chloride magnesium-sodium types of chemistry. The presence of toxic alkalinity in soils is associated with sodium supplied with irrigation water. The chloride-sulfate, sulfate-chloride type of chemistry is typical for zonal chestnut soils. The degree of salinity for these types of salt chemistry was determined with the following scales (Fig. 2).

Figure 3 shows the main relief elements of the key area necessary for the map analysis. Soil-salinity maps were constructed for the soil horizons at depths of 0–30, 30–50, 50–100, 100–150, and 150–200 cm (Fig. 4).

Analysis of the soil-salinity maps showed the following.

The value of the weighted average sum of toxic salts at a soil thickness of 0–30 cm on the side of the hollow above the main slope characterizes salinization of a weak degree (0.05%) of the chloride and chloride-sulfate type of chemistry. The soils throughout the rest of the area are defined as nonsaline (0.01–0.04%).

In the place of the former solonchak at a depth of 30–50 cm, alkaline salinization of a weak degree (0.05–0.07%) is observed, and a medium–weak degree (0.05–0.16%) of chloride and sulfate-chloride

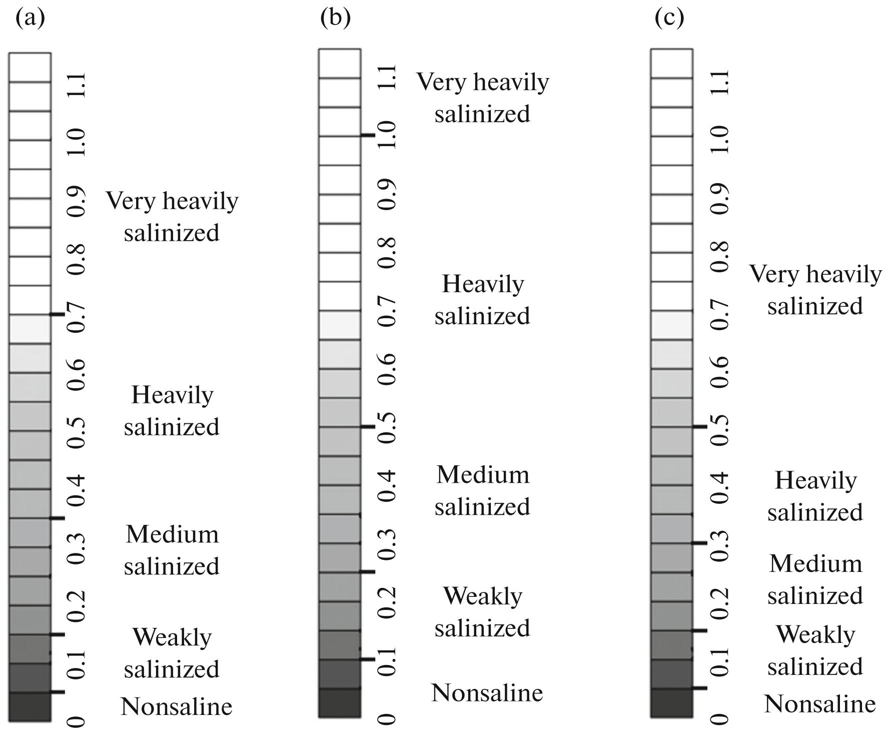

Fig. 2. Scales for the degree of soil salinity (according to Stox, %): (a) chloride, chloride-sulfate; (b) sulfate-chloride; (c) chloride-alkaline, alkaline-chloride (*Zasolennye pochvy*…, 2006).

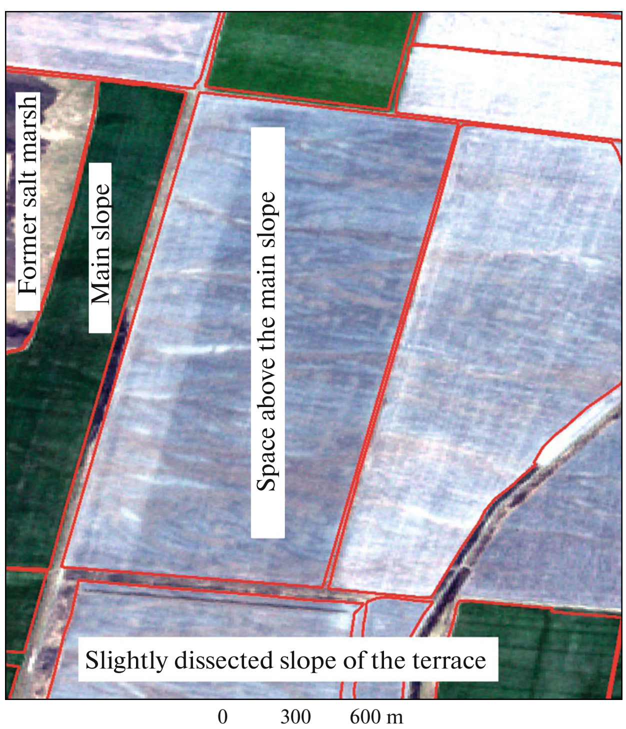

Fig. 3. Main relief elements of the key GIS area as marked on the Sentinel-2 satellite image from March 28, 2020.

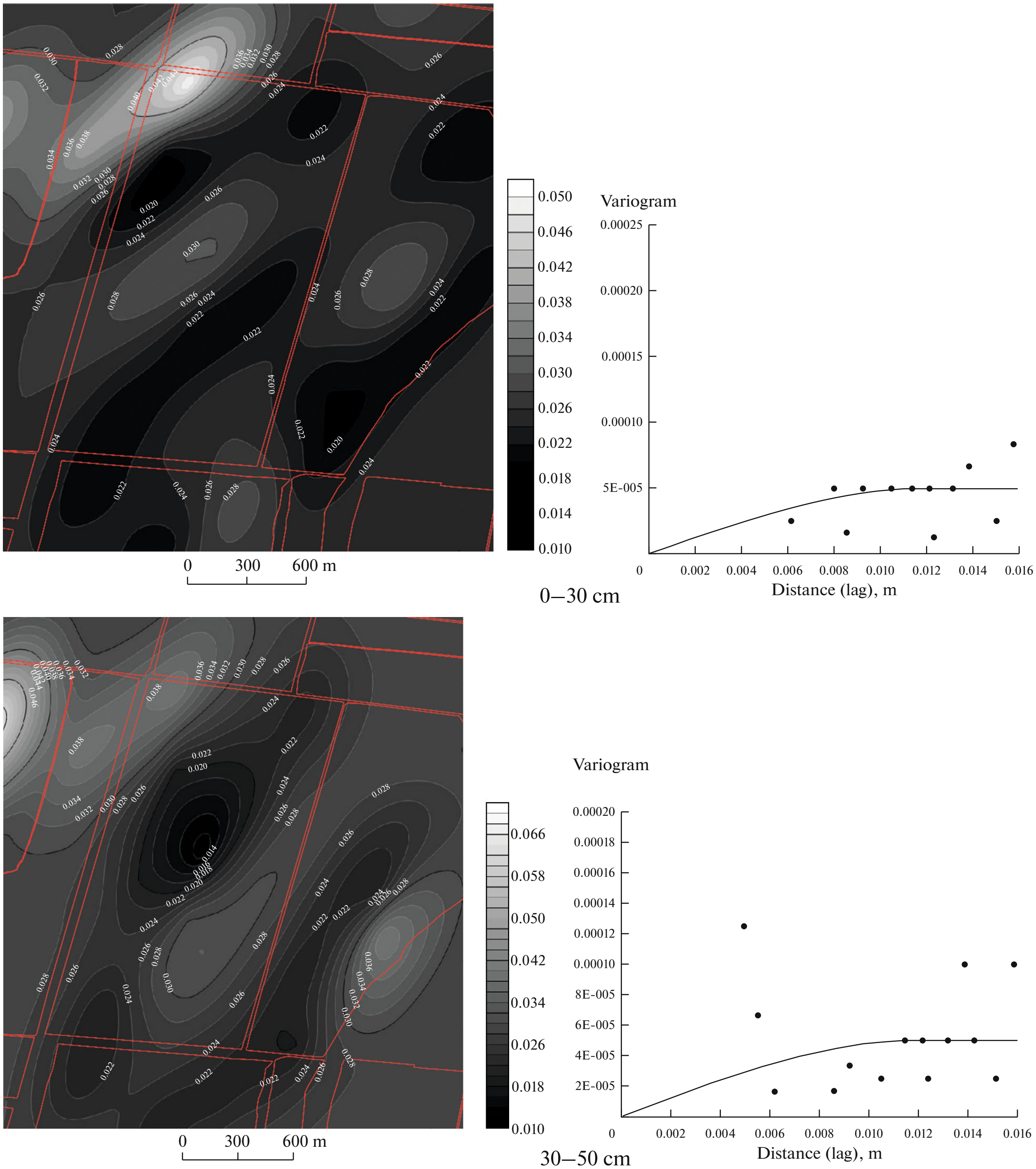

Fig. 4. Variograms and maps of the spatial distribution of the content of the weighted average sum of toxic salts (S_{tox}, %) in the layers 0–30 and 30–50 cm in the key GIS area.

chemistry of salts is observed at a depth of 50–100 cm. In the 1990s, there was an open surface here with a GWL of <1.5 m, and the soils were strongly saline in the 1-m thick layer. This means that, in comparison with the previous period, there is a significant decrease in soil salinity at the site of the solonchak and around it, which is associated with a 30-year absence of irrigation. At present, the field with the former salt marsh is not cultivated and is completely overgrown with reeds. Soil salinization is not recorded (0.01–0.04%) in the rest of the area of the key area.

In the place of the former solonchak and outside it, on the side of the hollow above the main slope at a depth of 100–150 cm, the soil salinization is of a

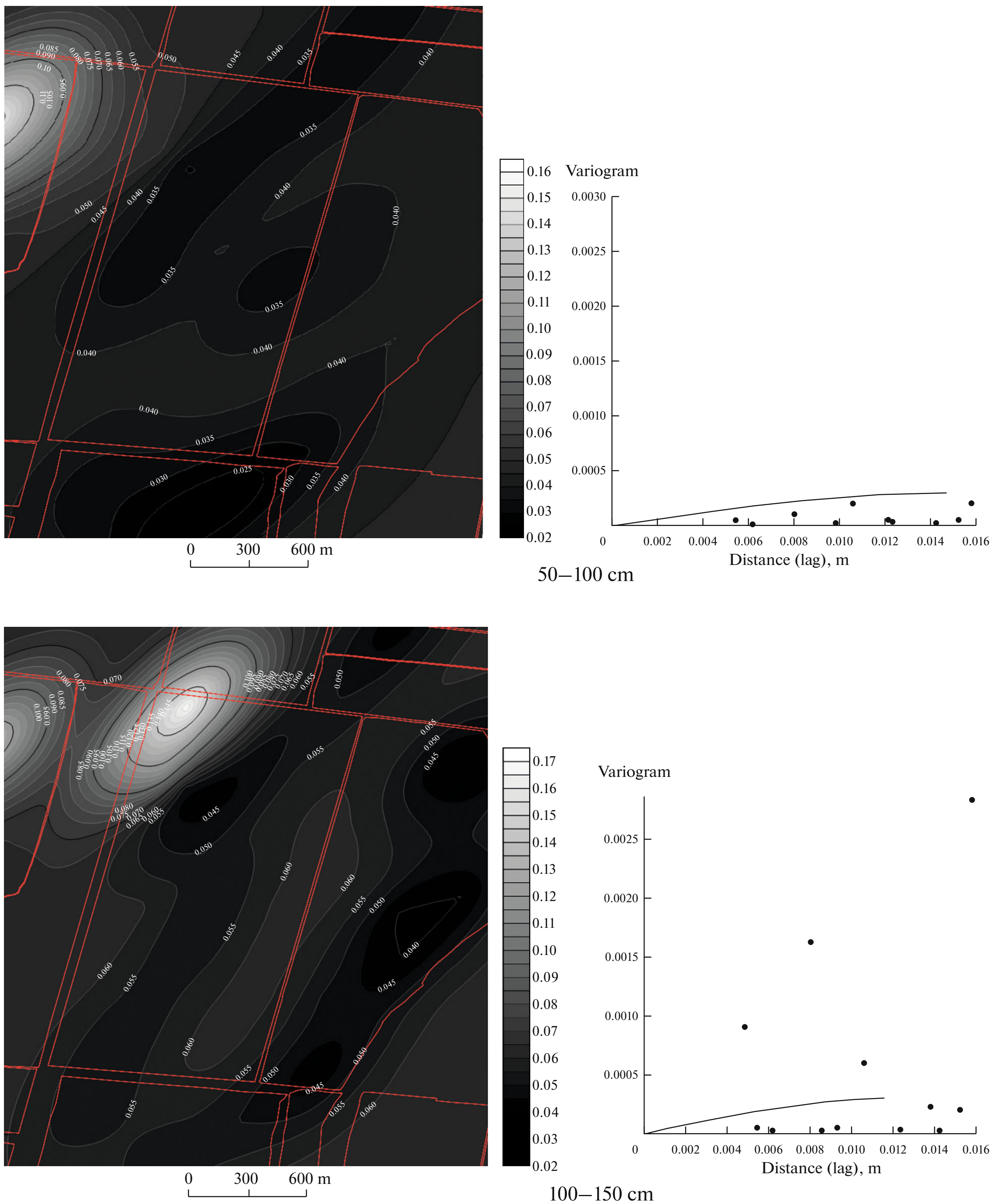

Fig. 4. (Contd.).

weak–medium degree (0.11–0.17%) of sulfate, alkaline, and chloride types of chemistry.

At a depth of than 150 cm, there is a weak–medium salinity (0.05–0.23%) of predominantly chloride and chloride-sulfate chemistry of salts. It occurs throughout the key area, which corresponds to the zonal features of chestnut soils in the dry steppe zone.

Thus, analysis of the maps of the key area with different salinity conditions by horizon showed the presence of soil salinization in a weak–medium degree at

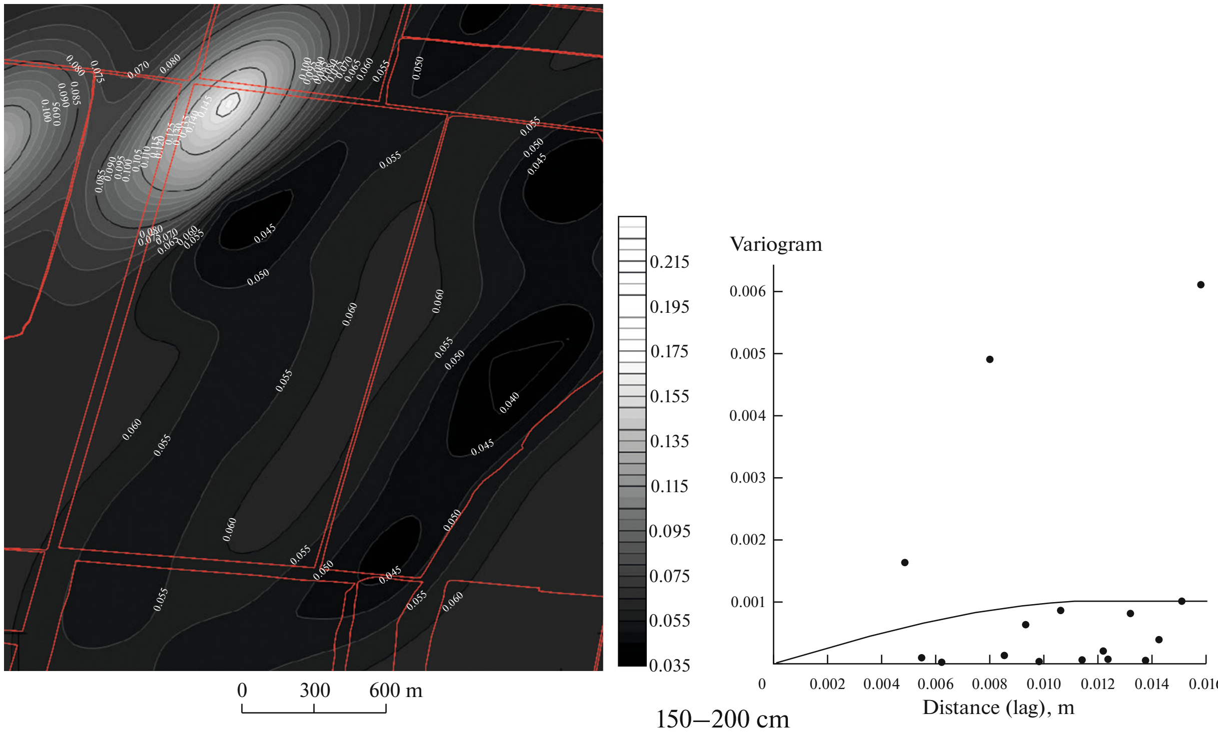

Fig. 4. (Contd.).

the site of the former solonchak, and, on the side of the hollow above the main slope to a depth of 150 cm, it showed significant desalinization of the former solonchak at a 1-m thickness, an absence of soil salinity around the former solonchak, and the development of alkalization of the upper horizons (up to 50 cm) of modern soils, which is associated with the location of the GIS in the solonetz zone and the accumulation of sodium in the soil as a result of irrigation in the past from the Tsimlyansk reservoir.

The identified processes of soil degradation require the development of systems of measures to stabilize the environmental sustainability of the agricultural landscape and to increase the soil productivity. Preliminary recommendations for the solution this problem upon the resumption of irrigation can include quality control of the irrigation water, the use of periodic (once every several years), water-charging spring washing of the 0- to 70-cm layer to push the accumulated salts out of the aeration zone, gypsum to ensure the displacement of exchangeable sodium, the suppression of alkalinity and the removal of water-soluble sodium into the underlying horizons beyond the root layer, the use of drip irrigation, and an increase in the share of more salt-tolerant perennial legumes and cereals in the structure of sown areas.

CONCLUSIONS

The article presents the results of studies carried out to identify the current salt state of the soils of the GIS, which is located in the dry-steppe zone of chestnut soils of Volgograd oblast in the Don Valley. The GIS was built on the basis of the Tsimlyansk reservoir in the middle of the last century. It is currently in a 30-year irrigation shutdown period, with the prospect of irrigation resumption in the coming years. The modern key research site was located within the second terrace of the Don River, where field works were carried out in August–September 2020 with the selection of soil samples. The materials of field surveys and the results of water extraction (1 : 5) of soil samples, together with the materials of the VHLRE, were used to build interpolation maps of the soil salinity that cover soil horizons of different depths and reflect the current salinity of the soils of the irrigation system.

The key area of study included a territory in which a high groundwater level (1.5–3 m) and strong mineralization (3–10 g/L) formed in the early 1990s during a long period of irrigation. This led to the formation of a meadow solonchak and secondary saline soils with a high degree of salinity, which prompted the mapping of soil salinity in this area to reflect changes over the past period.

As a result of the analysis of materials (VHLRE) and the soil-salinity maps compiled by the authors, it was found that the 30-year period of cessation of irrigation throughout the irrigation system coincided with a deepening of the groundwater level to more than 5 m and a gradual desalinization of secondary saline soils from strong to weakly medium the degree of salinity, which is noted from a depth of 30–50 cm at the site of the former solonchak and the absence of salinity around it; deep (>150 cm) soil salinization was revealed throughout the entire area, which is typical for zonal chestnut soils and the development of alkalization of the upper horizons of modern soils. This is associated with the location of the GIS site in the solonetz zone and the accumulation of sodium in the soil as a result of irrigation in the past from Tsimlyansky reservoirs.

Studies have shown that interpolation methods can be used for soil-cover maps that reflect the depth of the salt horizon (especially the first from the surface) and contain information that is necessary for the development and selection of optimal reclamation measures to restore the soil fertility.

An attempt to use the spectral indices of soil salinity from remote information from the literature did not give a positive result.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors declare that they have no conflicts of interest.

Statement on the welfare of humans or animals. This article does not contain any studies involving humans or animals performed by any of the authors.

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