
DEGRADATION, REHABILITATION,
AND CONSERVATION OF SOILS

Soil Salinity Status under Post-Irrigation Conditions at the Generalovskaya Irrigation System in Volgograd Oblast

N. B. Khitrov^a, * (ORCID: 000-0001-5151-5109), I. N. Gorokhova^a, **, and E. I. Kravchenko^a

^a Dokuchaev Soil Science Institute, Moscow, 119017 Russia

*e-mail: khitrovn@gmail.com

**e-mail: g-irina14@yandex.ru

Received February 7, 2022; revised March 9, 2022; accepted March 13, 2022

Abstract—The aim of this work is to evaluate recent changes in soil salinity status at the Generalovskaya irrigation system in the dry-steppe zone of Volgograd oblast of Russia on the second terrace of the Don River near the Tsimlyansk Reservoir. The studied area has not been irrigated since the mid-1990s. We have used materials of terrain soil survey of the area in 1990 and 2020; data on soil water extracts (1 : 5); measurements of the activities of Na⁺, Ca²⁺, and Cl⁻ ions with ion-selective electrodes in soil pastes with a moisture content of 40–45%; and aerial photographs (1990) and satellite image (2020). The studied area was subjected to secondary soil salinization in the 1990s due to the groundwater rise above the critical level. In 25 years after the cessation of irrigation, the groundwater table has descended to a depth of more than 5 m, and secondary-saline soils have been subjected to a gradual desalinization with the development of alkalization in the topsoil. The current soil salinity status inherits the pattern that existed 25 years ago, i.e., the spatial distribution of salts in the studied landscape is generally preserved. We have revealed the presence of calcium chlorides in some soils in 2020, which are identified as evidences of secondary salinization developed by the 1990s. It is shown that the catenary method of terrain soil survey may be used in combination with satellite information and digital data processing for mapping the soil cover under post-irrigation conditions. This enables the reflection of the main soil groups, the depth of the upper saline horizon, and the presence or absence of carbonates on the soil surface. Such information is necessary for the development and selection of optimal reclamation measures.

Keywords: post-irrigation soils, alkalinity of soils, activity of sodium ions, evidences of secondary salinization of soils, digital soil mapping

DOI: 10.1134/S1064229322080075

INTRODUCTION

Lands of the dry-steppe zone of Russia are actively used in agriculture for plowing, hayfields, and pastures. The soil cover of the zone is represented by various soil combinations, including large massifs of non-solonchic and solonchic chestnut soils on well-drained watersheds; chestnut–solonchic complexes (microcatenas) with different portions of solonchics under automorphic, semi-hydromorphic, and hydromorphic conditions; combinations and spotted patterns of meadow-chestnut and meadow soils of various salinity and alkalinity; and alluvial soils in river valleys. Many Soviet and Russian researchers have revealed the main regularities of the natural status of soils of the dry-steppe zone under virgin conditions and at the initial stages of active agricultural development: different types of solonchic complexes, their genesis, the mosaic pattern of salts in them, etc. [2, 12, 14, 15, 19, 28].

Large irrigation systems were constructed in the European Russia in the middle of the 20th century to ensure the food security of the country. Construction

was most intensive in the 1950s–1960s [33]. By the mid-1980s, the number of developed irrigated lands became maximal. However, significant irrigation rates and the absence of drainage systems resulted in the groundwater level (GWL) rise, secondary salinization and alkalization of soils, flooding, and other adverse phenomena in the 1990s.

These were the reasons to study GWL fluctuations and rise during irrigation [1, 11, 24, 27], erosion of irrigated soils [20, 21], secondary salinization [12, 18], degradation of soil structure at macro- and microlevels [27], solonchicization [12], carbonate accumulation [4, 22, 23, 31], and the effect of irrigation waters on soil properties [5, 10, 13].

In recent years, the classical methods of studying saline irrigated soils are supplemented by the application of electromagnetometers for contactless assessment of soil salinity [36, 37] and by remote sensing with the use of high-resolution satellite information [7, 41, 42], data of unmanned aerial vehicles [40], and remotely determined parameters: vegetation indices, soil salinity and moisture, surface temperature, and topography.

Widely used models for the calculation and mapping of soil salinity include: random forest (RF), multiple linear regression (MLR), support vector machine (SVM), and artificial neural networks (ANN) [8, 38–41, 43]. Algorithm, which could perfectly work for the entire data set, is absent, so the one that corresponds to particular goals and may be used for the research area has been chosen [8, 41].

The use of remote and calculation methods for determination of the modern status and prediction of the spread of saline soils is especially important for inaccessible areas, because they improve the management strategy of the entire irrigated complex and save time and reduce cost of terrain and laboratory studies.

The area of irrigated land in Russia has been rearranged and significantly reduced since the 1990s: large massifs were abandoned and transformed into long-term fallows, another part of the lands was used for rain-fed farming, some areas were again irrigated only after a long period of fallow or after rain-fed use, and the irrigation technique of others was changed. Such great modification in the use of irrigated lands strongly affected soil properties, including the salt status: the composition, content, and spatial distribution of easily soluble salts, exchangeable cations, carbonates, and gypsum. The Generalovskaya Irrigation System (IS) located in the dry steppe zone of Volgograd oblast is an example.

The Generalovskaya IS with an area of 12439 ha and with water intake from the Tsimlyansk Reservoir was constructed in 1959 [33]. Irrigation was stopped there in the early 1990s. It was characterized by a high GWL, the development of secondary salinization on the background of the preserved natural local salinization of solonetzic associations, and the formation of solonchaks [6].

According to data of the Volgograd Hydrogeological Reclamation Party (VGRP), the area of agricultural land of the Generalovskaya IS is now 4870 ha. The lands are used for rain-fed agriculture, and there are prospects to restart irrigation. Winter cereals and technical crops (mustard) are cultivated, and there are still many fallow lands.

The aim of this research is to assess the trends of post-irrigation changes in the salt status of soils at the Generalovskaya IS, which became secondary saline in the 1990s and are not irrigated during a 25-year period. For this, the following tasks are set: (1) to study the current salinity of soils; (2) to compare the salt status of soils in two periods; and (3) to map the soil cover.

OBJECTS AND METHODS

The research object is represented by soils of the Generalovskaya IS located in the south of Volgograd oblast (Fig. 1). The Generalovskaya IS is mainly allocated to the second floodplain terrace of the Don River (the left bank) and partly to the northwestern

slope of the Ergeni Upland in the zone of insufficient moistening. The mean annual precipitation varies from 270 to 300 mm, 2/3 of which occurs in the warm period of year, and evaporation exceeds the annual precipitation two–three times [9].

The left-bank series of the Don terraces is represented by slightly inclined and rather similar areas with the altitudes of no more than 60 m. The width of the second floodplain terrace is much smaller than that of the third one, and the first terrace is covered by waters of the Tsimlyansk Reservoir. All the terraces are composed of Archeda-Don and Tsimlyansk sands accumulated during melting of the Dnepr glacier and then buried under a thick layer of mantle loam.

Prior to irrigation, the GWL depth in the Don River valley ranged from a few meters to 10 m [9]. According to the data of the VGRP, the GWL rose by the 1990s and reached 1.5–3 m at the irrigation system and 3–5 m in the Don River valley. Groundwater mineralization increased from 1–3 to 3–10 g/L. Its chemical composition was variegated and dominated by sulfates and chlorides in different combinations. At the present time, the GWL depth in the entire area of the Generalovskaya IS is >5 m. Changes in the chemical composition of groundwater during the irrigation period were not revealed.

The soil cover of the entire area of the Generalovskaya IS is represented by soil combinations. Chestnut nonsolonetzic and solonetzic soils with spots of solonchaks are formed on convex and relatively flat surfaces, and meadow-chestnut soils occupy micro-depressions and bottoms of wide hollows.

Some soils of the Don River terrace underwent significant changes during the irrigation period. Not deep GWL (1.5–3 m) and increased water mineralization (3–10 g/L) caused the transformation of meadow-chestnut soils into meadow solonchaks in the late 1980s–early 1990s. Their area was several hectares. Secondary strongly saline soils were formed around them.

In August–September 2020, terrain survey was performed at the Generalovskaya IS within the second terrace of the Don River. The described 16 soil pits and additional shallow pits characterized soil series along four catenas, which crossed the main slope from the watershed between wide hollows to the bottom of the hollow. Three soil-topographic profiles were described (Fig. 1b).

The test plot included three hypsometric levels of the river terrace slope slightly dissected by wide hollows directed towards the Tsimlyansk Reservoir: two catenas, across the slope at the altitude of 54–56 m (sites G-3–G-6 and G-9–G-13), one catena (sites G-21–G-24) at then altitude of 50–52 m; and the former solonchak at the altitude of 46.0–46.5 m (sites G-26 and G-27).

According to the data of State Design Institute for Land Management, the soil cover prior to irrigation was represented by chestnut solonetzic complexes, which

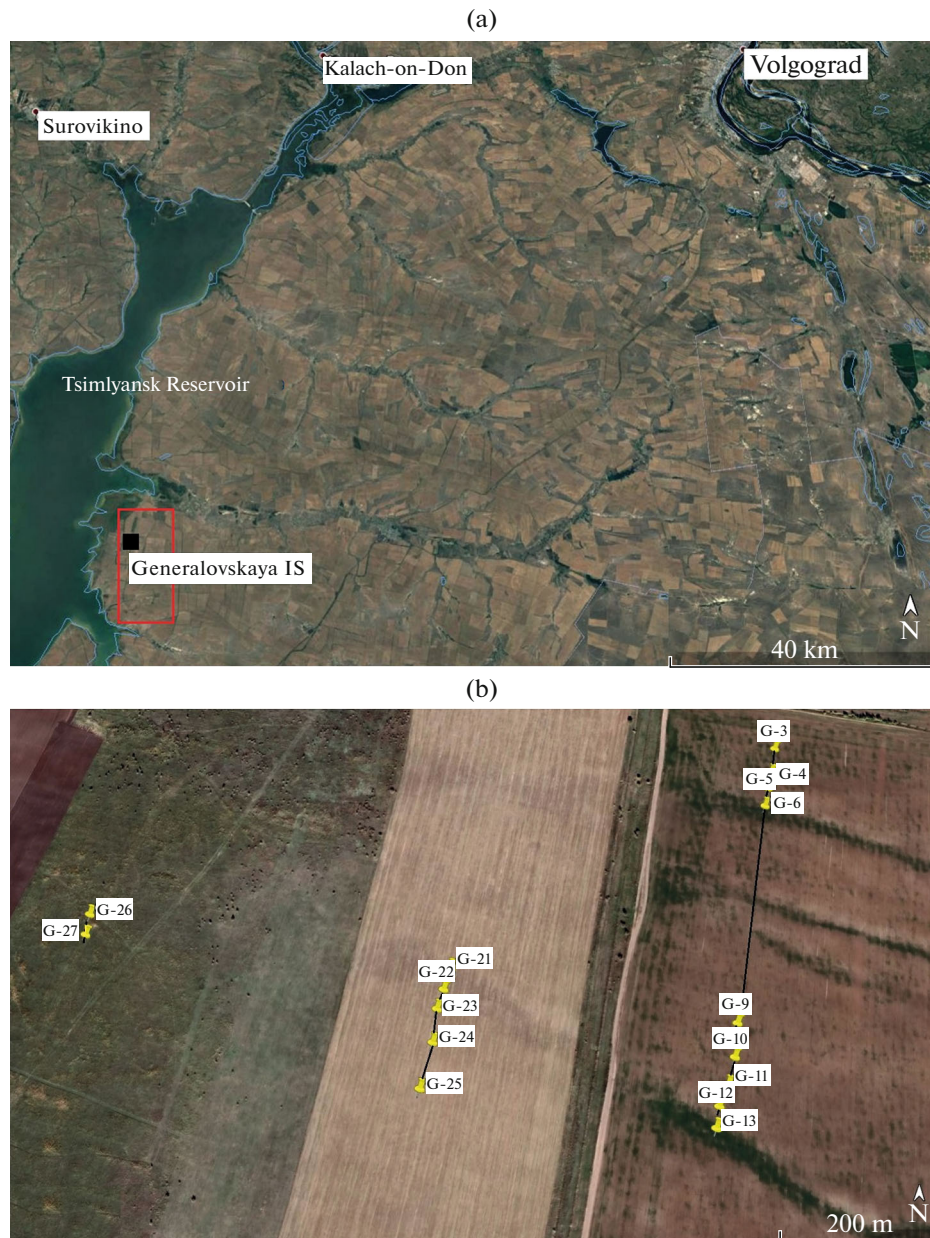


Fig. 1. (a) Location of the Generalovskaya IS and surveyed plot (black square); (b) sampling sites and soil-topographic profiles (catenas) at the test plot studied in August–September 2020. Satellite image of the test plot is taken from the Google Earth portal (September 27, 2018).

included predominating chestnut solonetzic and non-solonetzic loamy soils and 10–25% of medium and deep chestnut solonetztes and combinations of chestnut soils with meadow- and meadow-chestnut soils in hollows. The surface of fields was leveled for the surface irrigation during the construction of the system. The soils were irrigated during more than 30 years until the early 1990s.

Guidelines for the morphological description of soils [3, 30, 35] were used during the terrain survey, and soil names were given according to three classification systems: system of the USSR [16] (hereinafter, C-1977), of Russia [17, 26] (hereinafter RC-2004(8)),

and the international WRB system [34] (hereinafter WRB-2015).

The materials obtained in the 1990s and used by us included data on the salt content in water extract 1 : 5 in 0- to 50-cm and 50- to 100-cm layers from 18 geographically fixed soil pits, a panchromatic aerial photograph (on a scale of 1 : 25000, Soyuzgiprovodkhoz, June 23, 1990), and the results of semi-automatic remote diagnostics of soil salinity. The test plots differed in the combination of characteristics of the ameliorative status of lands: GWL, the status of crops, and soil salinity.

The content of water-soluble salts in soils studied in 2020 was determined in a standard water extract with the soil to water ratio of 1 : 5 (72 samples) and by measurements of the activity of Na^+ , Ca^{2+} , and Cl^- ions in soil pastes with the water content of 40–45% [29], using ion-selective electrodes (226 samples). Soil salinity was determined by gradations of Na^+ activity in soil pastes: <20 mmol/L—nonsaline, 20–50 mmol/L—slightly saline, 50–150 mmol/L—moderately saline, 150–300 mmol/L—strongly saline, and >300 mmol/L—very strongly saline soils. Secondary salinization was conventionally indicated by the ratio between the activities of ions, when the chloride ion activity exceeded the Na^+ activity, and the activity of Ca ions was high (to 10–15 mmol/L), which testified to the presence of calcium chloride in the soil solution. The portion of exchangeable Na (N_{exch} %) was estimated by the ratio between the activities of Na (a_{Na}) and Ca (a_{Ca}) ions according to a special regression model [32]. The ion composition of water was determined by conventional methods [29].

A satellite image from Yandex.ru (28.03.2020, Pleiades) portal was used to extrapolate areas of soil units and compile a soil map for the test plot. The image was processed by the ENVI 5.1 software package, using the standard ISODATA algorithm, the classifier of which was based on the statistical cluster analysis of k-means. The Euclidean distance was used as a measure of proximity. The program divided the data by classes, using the maximal, mean, and minimal brightness and standard deviation in the first iteration, and then, means and the minimal Euclidean distance were applied for the classification until the optimal separation of classes has been obtained.

RESULTS AND DISCUSSION

General features of the soil profiles. Modern soils include the P agrohumus horizon from 24 to 45 cm thick with the median of 33 cm and the lower and upper quartiles of 30 and 38 cm, respectively. It consists of two or three horizons, differing in effervescence with HCl, alkalinity, structure, and the presence of in-plowed fragments of the underlying horizon.

The lower part of the BMKsn xerometamorphic solonetzic horizon is preserved just under the plow layer in several pits (G-4, G-5, G-9, G-11, G-22, and G-25). It is characterized by prismatic structure and humus-clay coatings on the lateral pedfaces. Humus-clay coatings on the blocks in the plow horizon of soils of two catenas located in their upper parts at the altitude of 54–56 m indicate the active phase of the current development of solonetzic process. At lower levels of the general slope (at the altitude of 50–52 and 46–47 m), morphological features of alkalinity are few (Figs. 2, 3).

All soils of the three catenas at the altitudes between 50 and 56 m include the carbonate-accumulative BCA

horizon characterized by continuous effervescence with HCl of the soil mass; it has also secondary carbonates (beloglazka). The BCA horizon thickness varies from 20 to 75 cm with the median of 44 cm and the lower and upper quartiles of 38 and 54 cm. The highest and lowest values are typical for soils of hollow bottoms, in which the upper boundary of the BCA horizon is located in the depth interval 80 to 140 cm. These are clay-illuvial agrozems (pits G-6 and G-21) and agrodark-humus clay-illuvial heavy loamy soils (pit G-13) on loess-like loams (meadow-chestnut soils according to C-1977; Luvic Kastanozem (Loamic, Aric)) in WRB.

Chestnut soils (according to C-1977) having had similar profiles prior to the intensive anthropogenic impact are now specified into two soil types according to RC-2004(8): agrochestnut soils with the preserved BMK xerometamorphic horizon and carbonate-accumulative segregationary agrozems without BMK horizon. Agrochestnut soils on the plot are qualified for solonetzic (Luvic Kastanozems (Loamic, Aric, Protosodic, Bathygypsic)); while agrozems are either solonetzic (Luvic Kastanozems (Loamic, Aric, Protosodic, Bathygypsic)), or nonsolonetzic (Haplic Kastanozems (Loamic, Aric, Bathygypsic)).

In 2020, light-humus carbonate-accumulative clay-illuvial postagrogenic, oxigleyic, effervescing and gypsum-bearing in the middle part, pyrogenic slightly saline, and solonchakous medium-loamy soils on yellow-brown stratified loams were revealed under the community of reed and wheat-grass. Presumably, they were formed in place of the meadow solonchak, which, in turn, originated from a meadow-chestnut soil during irrigation in the 1980s–1990s due to the GWL rise to a depth of <1.5 m. This means that there were two stages of soil evolution during a short time period (less than half a century): intensive salinization and subsequent desalinization.

Since irrigation of the Generalovskaya IS planned again, we have analyzed the composition of water near the water intake facility (now inactive) in the settlement of Pugachevskii located at the mouth of the Esaulovskii Aksai River, flowing into the Tsimlyansk Reservoir (Table 1). This is a steppe river with the catchment basin on the western slope of the Ergeni Upland with solonetzic micro-associations. As a result, water in the river is slightly saline (3.9 g/L, and SAR = 9.7). Irrigation by this water will cause accumulation of exchangeable sodium to 10–12% of the CEC and secondary solonetzization, as well as the secondary accumulation of easily soluble salts in the root zone to the rate of weak salinization. Thus, irrigation with water of such composition requires special measures for improving water quality in order to prevent adverse processes.

The salt status of soils of catenas G-3–G-6 and G-9–G-13 at the altitude of 50–56 m. Let us consider changes in salinization of formerly irrigated soils on the test plot after the 25-year-long period without irri-

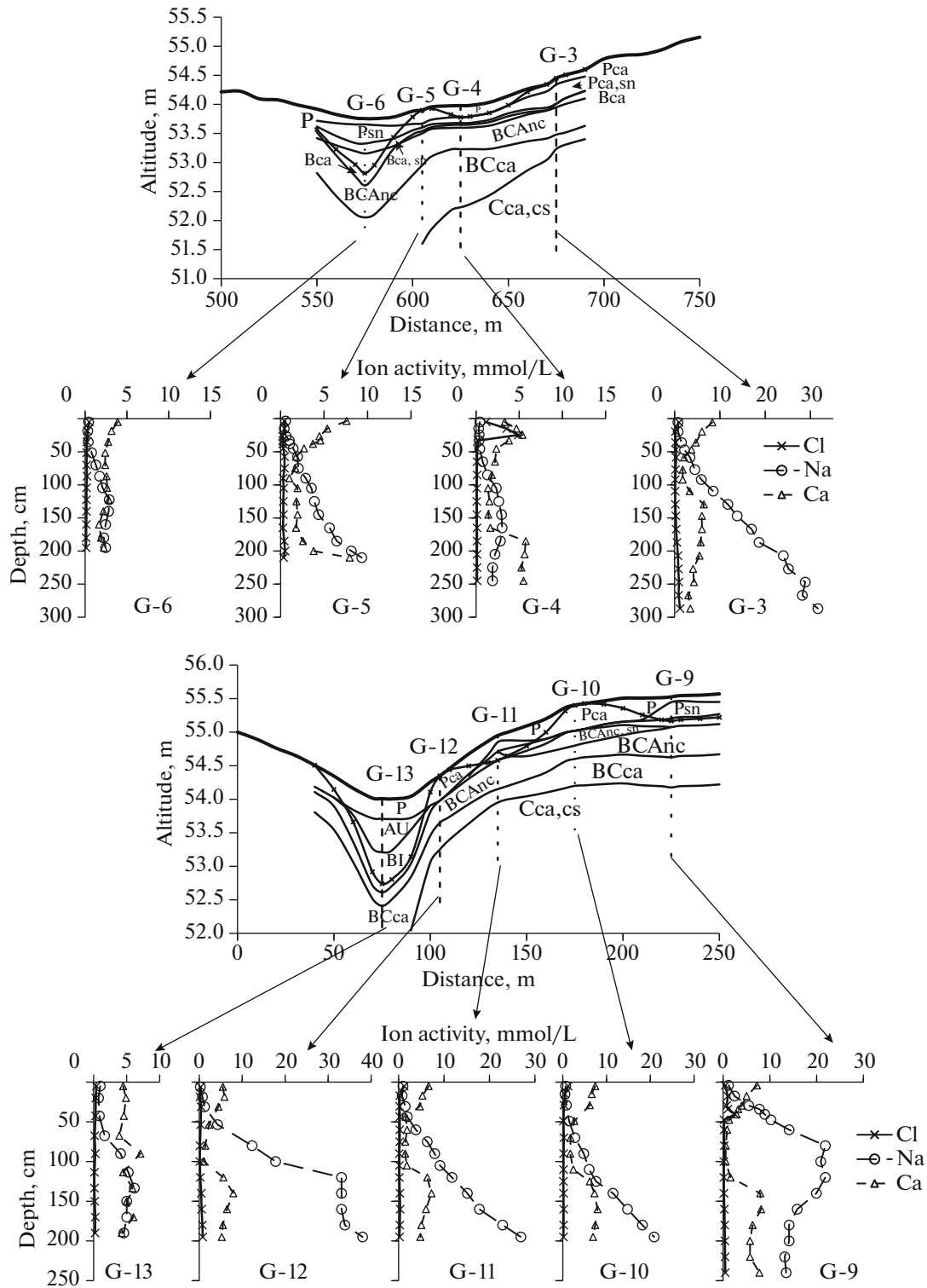


Fig. 2. Soil profiles along the catenas G-3–G-6 and G-9–G-13 and the vertical distribution of the activity of Na^+ , Ca^{2+} , and Cl^- ions measured in soil pastes with the water content of 40 wt %.

gation. The GWL on the field located higher than the main slope of the second terrace of the Don River at the altitude of 54–56 m (pits G-3–G-13) was at the depth of 3–5 m during irrigation in 1990s and is now

deeper than 5 m. The soil association is characterized by more frequent occurrence of solonchaks, where the humus-clay coatings on pedfaces of blocks are identified even in the plow horizon (G-3–G-6, G-9).

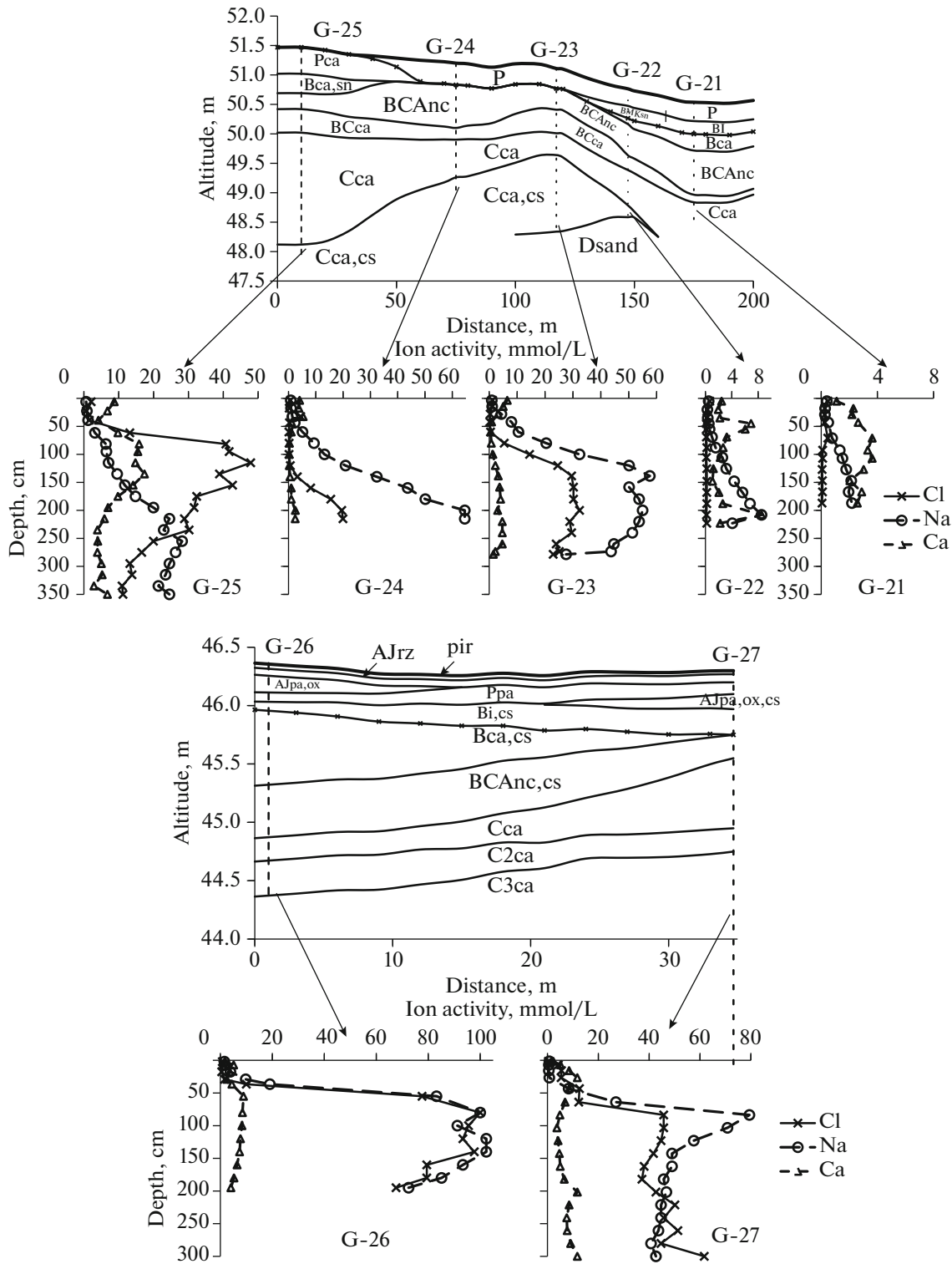


Fig. 3. Soil profiles along the catenas G-21–G-25 and G-26–G-27 and the vertical distribution of the activity of Na⁺, Ca²⁺, and Cl⁻ ions measured in pastes with the water content of 40 wt %.

According to data on the activity of ions in pastes, soils in the bottoms of hollows and on the adjacent lower part of the slope at the height less than 20 cm relative to the bottom are not saline to a depth of more than 2 m. The Na⁺ activity does not exceed 3–7 mmol/L (or

0.12–0.28 cmol(c)/kg), and the Cl⁻ activity is less than 1 mmol/L (<0.04 cmol(c)/kg).

The depth of slightly saline soil horizons on convex slopes between the hollows ranges from 80 to 170 cm,

Table 1. Salt composition of water at the mouth of the Esaulovskii Aksai River at its discharge into the Tsimlyansk Reservoir near the water intake (not functioning now) of the Generalovskaya IS (sampling on September 1, 2020)

| pH | HCO ₃ ⁻ | Cl ⁻ | SO ₄ ²⁻ | Ca ²⁺ | Mg ²⁺ | Na ⁺ | K ⁺ | Total salts, g/L | EC ₂₅ , dS/m | SAR |
|-----|-------------------------------|-----------------|-------------------------------|------------------|------------------|-----------------|----------------|------------------|-------------------------|------|
| | mmol(c)/L | | | | | | | | | |
| 7.8 | 1.8 | 27.1 | 33.4 | 15.5 | 11.8 | 35 | 0.2 | 3.93 | 5.42 | 9.47 |

which corresponds to solonchakous, deep-solonchakous, and deep-saline varieties. Soils with the saline horizon deeper than 1 m predominate. The vertical distribution pattern of salts in these soils (G-3, G-10, and G-11) is deep-accumulative with a relatively gradual increase in the activity of sodium ions down the profile and its maximum at the depth of 180–200 cm. In the lower part of the slope at the side of a deeper hollow (G-12), the distribution of sodium activity is also deep-accumulative, but the upper saline horizon is closer to the surface than on the top parts of the slope.

Only pit G-9 is assigned to solonchakous varieties: it is characterized by Na⁺ accumulation in the middle part of the profile with the maximum at a depth of 80–130 cm. According to data on the water extract, the salinity is mainly of sodium-magnesium sulfate type, and gypsum is often present.

The upper two catenas are characterized by a specific vertical distribution of Ca²⁺ ion activity with the minimum (0.5–2 mmol/L) in the middle part of the profile and two maxima (5–8 mmol/L) in the upper nonsaline and lower saline horizons. The nonsaline soils in the bottoms of hollows are exceptions; the Ca²⁺ activity in them is characterized by almost uniform vertical distribution and varies within 3–7 mmol/L.

The minimal Ca²⁺ activity in the middle part of the soil profile indicates an increased alkalinity of the soil solution formed during desalinization of formerly saline horizons. It is accompanied by low toxic alkalinity related to Na in nonsaline horizons revealed in the water extract.

The plot, with G-3–G-6 catena was characterized by a good status of cultivated crops with an extremely rare manifestations of salinization in the 1990s (Fig. 4, Table 2). These areas with a homogeneous phototone are designated in Fig. 4 by number 1. The adjacent plot with G-9–G-13 catena was characterized by mosaic salinization that caused death of crops. It is designated by number 2 in Fig. 4.

The assessment of the salt status of soils in 2020 enables us to assume that the difference between the plots has been preserved in deeper horizons. Slightly saline horizons with gypsum in soils of catena G-9–G-13 are located at a smaller depth.

The salt status of soils of catena G-21–G-25 at the altitude of 50–52 m. Let us analyze the status of soils on the main slope of the second terrace of the Don River in the field, where the GWL in the 1990s was at

a depth of 1.5–3.0 m and some part of soils was solonchakous.

According to terrain survey of 2020, the soil cover pattern is qualified for combination-spotted. Bottoms of wide hollows are occupied by clay-illuvial agrozems (meadow-chestnut soils or Luvic Kastanozems (Loamic, Aric)). Agrochestnut solonetzic (chestnut solonetzic plowed soils or Luvic Kastanozem (Loamic, Aric, Protosodic)) and silty loamy carbonate-accumulative agrozems (chestnut plowed eroded soils or Haplic Kastanozem (Loamic, Aric, Protosodic)) on pale brown loess-like loam underlain by sand from a depth of 2–2.5 m are formed on slightly convex inclined slopes between the hollows. In some places, soils are strongly burrowed by animals (zooturbated), and there are also stratified soils with carbonate material translocated to the surface during leveling.

Solonchakous (pits G-23, G-25) and deep-solonchakous (pit G-24) soils with the upper boundary of the slightly saline horizon at depths of 70–80 and 110 cm, respectively, occur on the weakly convex surface between hollows. According to data of the water extract, the salinization is chloride-soda or soda-chloride sodic with the sum of toxic salts (S_{tox}) of 0.08–0.09%. In horizons with morphologically evident fine-crystalline gypsum veins at a depth of 150–200 cm, the salinization type becomes chloride-sulfate magnesium-sodic with gypsum. The salinity rate varies from slight to medium (S_{tox} = 0.15–0.23%).

According to the measurement of ion activity in pastes, soils in the bottom and on the slopes of the wide hollow (pits G-21 and G-22) do not contain easily soluble salts to a depth of 2–2.5 m, including the entire layer of loess-like loams and underlying sands. The activity of chlorides varies from 0.06 to 0.6 mmol/L (0.002–0.02 cmol(c)/kg), and that of sodium ions is within 0.25–2.2 mmol/L (0.01–0.09 cmol(c)/kg) in the bottom of the hollow, and 0.3–8.5 mmol/L (0.01–0.34 cmol(c)/kg) on its slope and is characterized by a general trend to an increase down the soil profile.

The salinity distribution pattern with respect to sodium activity is deep-accumulative in the deep-solonchakous soil of pit G-24 and middle-accumulative in solonchakous soils of pits G-23 and G-25. The salinity in the lower part of the profile is slight and moderate. Its upper boundary determined by the Na⁺ activity is located at depths of 80 (pit G-23), 120 (pit G-24), and 195 cm (pit G-25). In comparison with soils of the upper catenas, the maxima of sodium

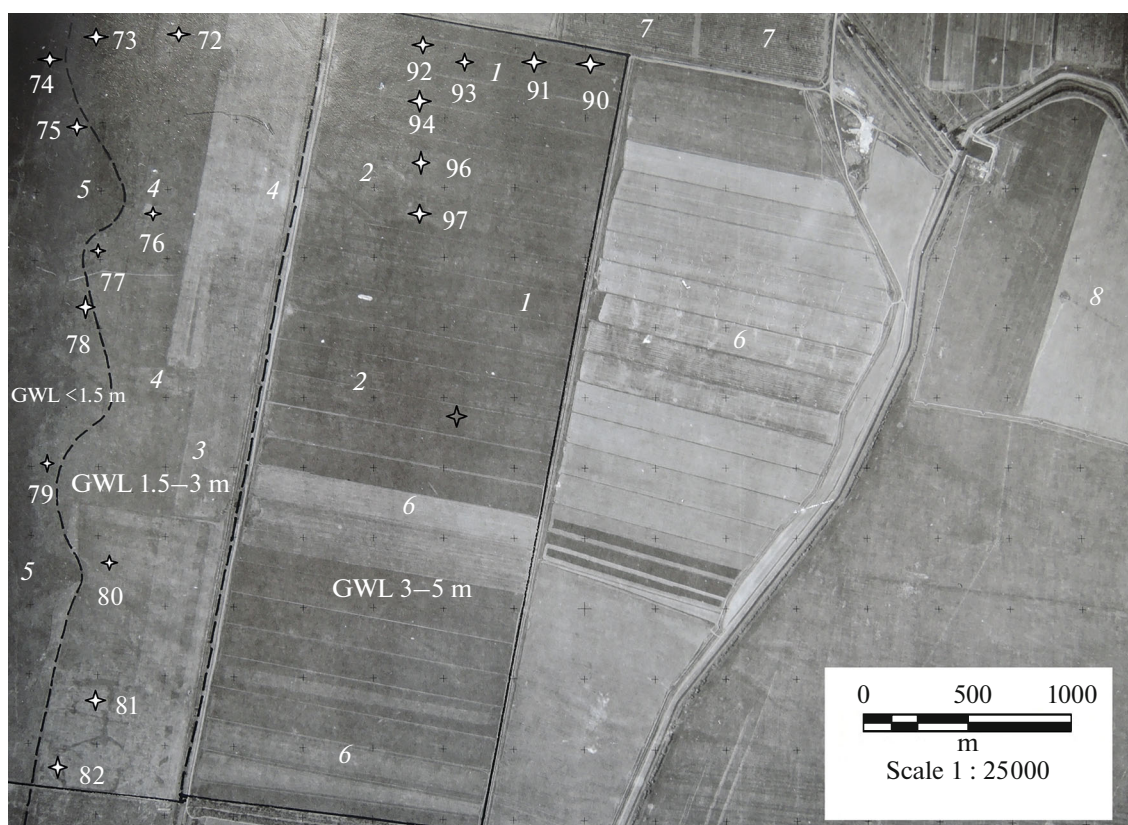


Fig. 4. The test plot of the Generalovskaya IS with groundwater level (GWL) zones in 1990: 3–5, 3–1.5, and <1.5 m in the image of the panchromatic aerial photograph (Soyuzgiprovodkhoz, June 23, 1990). Designations: (1) areas with alfalfa of good quality; (2) spots of thin alfalfa cover related to solonchak and erosion processes; (3) open surface and partially cut down grass cover; (4) spots of strongly saline soils; (5) meadow solonchak; (6) harvested alfalfa; (7) gardens; (8) non-irrigated lands; 72–97, numbers of sampling sites for soil salinity in 1990 (Table 2).

ion activity here are larger: 50–60 mmol/L (2–2.4 cmol(c)/kg).

Pit G-25 has a specific feature. There is a maximum of Cl^- activity (40–48 mmol/L) in the 80- to 150-cm layer, corresponding to slight salinity. The activity of chlorides at this depth exceeds four times the activity of Na^+ ions (7–12 mmol/L). Chlorides in the solution are compensated by Ca^{2+} , whose activity in this layer is 15–18 mmol/L (which corresponds to 30–36 meq/L). The activity of chloride ions gradually decreases with depth, and does not exceed the activity of Na^+ ions from a depth of 250 cm. The presence of calcium chlorides is a residual feature of secondary salinization [25]. In the 1990s, this field was partially developed, the GWL depth was 1.5–3 m, which favored the rise of the capillary fringe to the root zone. The field of alfalfa had a spotty pattern, and some plants died in places of strong secondary soil salinization.

In pits G-23 and G-24, where Na^+ activity exceeds that of Cl^- , the vertical distribution of Ca^{2+} activity is similar to that described above for pits of the two upper catenas: there is a minimum (0.3–0.5 mmol/L) in the middle part of the profile and

two maxima (3–6 mmol/L) in the upper and lower horizons. This is the evidence of alkaline conditions in carbonate-accumulative horizons of the studied soils, which is confirmed by the data of water extract. According to them, the salinity is of sodium chloride-soda type with a high portion of total alkalinity among anions and toxic alkalinity related to Na. It is replaced by chloride-sulfate magnesium-sodium salinization with gypsum in deeper layers.

Thus, the upper horizons of solonchakous strongly saline soils in the area with not deep GWL underwent partial desalinization over the 25-year period after the irrigation stopped, while local traces of the former secondary salinization were preserved in the form of Ca chlorides in soil solutions. The content of easily soluble salts in soils of this catena is higher and they occur higher in the soil profile as compared to the two upper catenas.

The salt status of soils in the area of the former solonchak. Pits G-26 and G-27 were dug in the area of the former meadow solonchak, evolved from meadow-chestnut soils, where the GWL was <1.5 m in 1990s. The soils were strongly and very strongly saline in the upper 1-m-thick layer. The plot at the altitude of

Table 2. Soil salinity and chemical composition of salts on the test plot of the Generalovskaya IS in June 1990

| Site no. | Weighted mean of total toxic salts (%) in soil layer | | Chemical composition of salts | Salinity rate |
|----------|--|-----------|-------------------------------|---------------|
| | 0–50 cm | 50–100 cm | | |
| 72 | 0.79 | 0.88 | Chloride-sulfate | Strong |
| 73 | 1.02 | 1.11 | – | Very strong |
| 74 | 0.74 | 0.91 | – | Very strong |
| 75 | 1.10 | 1.39 | – | Very strong |
| 76 | 0.73 | 0.89 | – | Strong |
| 77 | 0.72 | 1.12 | – | Very strong |
| 78 | 0.91 | 1.15 | – | Very strong |
| 79 | 1.10 | 1.16 | – | Very strong |
| 80 | 0.52 | 0.82 | – | Strong |
| 81 | 0.67 | 0.78 | – | Strong |
| 82 | 0.76 | 1.14 | – | Very strong |
| 90 | 0.04 | 0.05 | Sulfate | Not saline |
| 91 | 0.03 | 0.04 | Chloride-sulfate | Not saline |
| 92 | 0.09 | 0.09 | – | Not saline |
| 93 | 0.04 | 0.07 | – | Not saline |
| 94 | 0.04 | 0.05 | – | Not saline |
| 96 | 0.14 | 0.14 | – | Slight |
| 97 | 0.08 | 0.13 | – | Slight |

46.0–46.5 m above sea level was the closest to the Tsimlyansk Reservoir. The field was completely overgrown by reed. Pit G-26 characterized a slightly convex background surface of the general gentle slope with sparse low (1.0–1.3 m) reed with wheat-grass and woodreed; pit G-27 was dug in the bottom of a shallow hollow with dense cover of reed 2–2.5 m high and with wheat-grass in the second layer. The soil cover was composed by meadow-chestnut old-plowed solonchakous, and heavy- and medium-loamy soils on pale-brown loams (C-1977), or by light-humus pyrogenic postagrogenic oxigleyic clay-illuvial, gypsum-bearing in high layers, carbonate-bearing in middle layers, with segregation carbonates in deep layers, and heavy- and medium-loamy soils on pale-brown silty loams underlain by stratified loams from a depth of 1.5 m (RC-2004) or Luvic Gypsic Kastanozems (Loamic, Oxiaquic, Endoprotosalic) in WRB.

Periodic burning of reed produced a 3–4-cm-thick pyrogenic layer (index *pyr*) on the soil surface, composed of charred plant residues with an admixture of mineral particles. During 30 years, the former plowed horizon was gradually transformed into the AJ light-humus horizon under the effect of the root systems of reed and wheatgrass. A sod (index *rz*) 4–6 cm thick was formed in its upper part. The partially preserved angular blocky structure of the first order with some angular irregularly shaped aggregates (index *pa*, which signifies postagrogenic) became friable, and was mainly

fragmented by roots into granular and flattened granular aggregates. Brown-rusty films of iron hydroxides on the faces of many aggregates and soft brown concretions 1–2 mm in diameter occurring in clusters up to 2 cm in size in block interiors indicate periodic reducing conditions in the surface horizon, which are replaced by oxidative ones in summer, when soils dry out (index *ox*, which signifies oxidized gley).

There is a noticeable amount of veins of farinaceous gypsum beginning from the depth of 21–33 cm and continuing to the depth of 75–150 cm in the AJpa,ox,cs, Bi,cs, Bca,cs, and BCanc,cs horizons. In the hollow (pit G-27), the gypsum layer is thinner and is located closer to the surface in large reed rhizomes. On a slightly convex surface (pit 26), gypsum features begin slightly deeper beyond the light-humus horizon and are recognizable to the depth of 150 cm.

The surface horizons of the former solonchak, excluding the newly formed pyrogenic ones, underwent desalinization by 2020 and formally became nonsaline. However, the activity of sodium ions in them ranges from 0.5 to 9 mmol/L at the humidity of 40 wt %, which indicates an uncompleted process. Desalinization on the main slope resulted in toxic alkalinity related to sodium, whereas a high total alkalinity in the hollow (0.5–1.0 meq/kg) is completely compensated by Ca, one of the sources of which is a grid of abundant veins of farinaceous gypsum at the depth of 20–33 cm.

The first slightly saline horizon begins from a depth of 33 cm on a weakly convex surface (pit G-26) and of 50 cm in a shallow hollow (pit G-27). The most part of the soil profile from 40–70 to 300 cm is characterized by medium salinity of the chloride calcium-magnesium-sodium or calcium-sodium type ($S_{tox} = 0.12–0.17\%$). On the main slope, the salt content is maximal in the middle part of the profile (from 40- to 70-cm deep) in the horizon of continuous effervescence with HCl, with veins of farinaceous gypsum and without secondary carbonates manifestations, which appear only from the depth of 105 cm. The distribution of salts in the hollow is mainly characterized by eluvial pattern with slightly varying amount of toxic salts (0.11–0.14%) within 1–3 m thickness.

However, the measurement data on ion activity in pastes show a particular maximum of the Na^+ and Cl^- content at a depth of about 1 m, where there is a large amount of medium and small roots and rhizomes of reed. Pits G-26 and G-27 are characterized by the highest values of Na^+ and Cl^- activity on the entire studied plot. Both pits have horizons with Ca and Mg chlorides, which evidence the secondary salinization from groundwater located close to the surface during the irrigation period.

It is important to find the reasons of the not deep GWL in the 1990s and of the recent formation of a wide strip of reed on the general slope of the second terrace of the Don River. The data of manual drilling testify that there are stratified loamy deposits from a depth of 130–150 cm, which favor water retention in some strata. They are soft-plastic, very viscous, and contain living reed roots of 5–6 mm in diameter, which supply water to aboveground plant organs. Two such strongly moistened layers were revealed in the 3-m-thick soil profile: the Cca and C3ca horizons (Fig. 3) separated by the C2ca horizon of silty loams with significantly lower moisture. Stratified loamy deposits on the terrace receiving additional water during intensive irrigation provided the formation of a long-term perched water table and the solonchak. At present, the same deposits under conditions of only atmospheric moisture supply maintain the development of reed-wheatgrass association.

Trends of the salt status of soils under post-irrigation conditions. The analysis of the modern salt status of soils performed in 2020 on plots of various initial (30 years ago) salt soil status enables the following conclusions. First, over the 25-year-long period without irrigation, secondary saline soils underwent gradual desalinization under the effect of atmospheric precipitation, and alkalization developed in their upper horizons. These processes were the most pronounced in the former secondary solonchak of the 1990s. Second, features of secondary salinization are preserved now on two plots, where GWL in the past was <3 m and salinity was the strongest. They are represented by Ca chlorides in soil solutions against the background

of a significant decrease in the GWL. Third, differences in the salt status among the soils of four plots are preserved. It may be concluded that the current salt status of soils is inherited from that of 25 years ago. Soils on the plot with a generally well developed alfalfa during irrigation, indicating the lowest salinity, are now nonsaline to a depth of 2 m, and only deeply saline varieties are rarely found. Areas with the spotty salinization pattern and different GWL (3–5 and 1.5–3 m) in the 1990s are now occupied by solonchakous and deep solonchakous soils with a relatively higher salt content and the presence of calcium chlorides on the initially more saline plot with the GWL of 1.5–3 m. The area of the former solonchak still remains the most saline.

Assessment of the areal distribution of soils by remote sensing data. Terrain diagnostics and description of soils, as well as soil classifications (C-1977 and RC-2004(8)), were used for clustering the satellite image (Pleiades, March 28, 2020) and extrapolation of soil types to a fragment of the interpreted image, covering a part of the test plot around catenas G-3–G-6, G-9–G-13, and G-21–G-25 of a total area of 71 ha (excluding the area of the canal and the road). The field with the former solonchak was not analyzed because of the small number of sampling sites (Fig. 5).

The soils were grouped according to the depth (from the earth surface) of the first salt horizon (to 30 cm—solonchakous; 30–80 (100) cm—slightly solonchakous; 100–150 cm—deep solonchakous; and 150–200 cm—deep saline) and by the effervescence with 10% HCl from the surface, which qualitatively reflected the presence or absence of carbonates in the plow horizon. Soil texture was determined during terrain survey.

Clustering of the image enabled us to distinguish the following groups of soils by the dominating features: (1) chestnut plowed (agrochestnut) solonchakous, and deep-saline silty loamy soils; (2) chestnut plowed (carbonate-accumulative agroze-m) solonchakous surface-calcareous solonchakous, and deep-solonchakous silty loamy soils; (3) meadow-chestnut plowed (clay-illuvial agroze-m) nonsaline silty loamy soils; (4) meadow- and meadow-chestnut plowed (agrodark-humus clay-illuvial and clay-illuvial agroze-m) nonsaline heavy and silty loamy soils; (5) meadow-chestnut (clay-illuvial oxigleyic agroze-m) solonchakous heavy and silty loamy soils (Fig. 5b).

The entire analyzed part of the test plot is plowed and crossed by many hollows (Fig. 5a). They are well seen on the modern satellite image, but are poorly visible on the aerial photograph of 1990. This is explained by the absence of field levelling in the post-irrigation period and the development of soil erosion.

Most of the general slope (67.9% of the total area), which forms the watershed between the hollows, is occupied by agrochestnut solonchakous deep-solonchakous deep-saline silty loamy soils (Fig. 5b, soils 1).



Fig. 5. (a) Satellite image from Yandex.ru (March 28, 2020, Pleiades) portal and (b) the result of its clustering and compiling a soil map of the studied plot. Designations: (1) plowed (agrochestnut) solonetzic deeply solonchakous deeply saline silt loamy chestnut soils; (2) plowed solonetzic surface-calcareous solonchakous and deep-solonchakous silty loamy chestnut soils (carbonate-accumulative agrozeems); (3) plowed nonsaline silty loamy meadow-chestnut soils (clay-illuvial agrozeems); (4) plowed nonsaline clayey and silty loamy meadow and meadow-chestnut soils (agrodark-humus clay-illuvial soils and clay-illuvial agrozeems); (5) solonchakous clayey and silty loamy meadow-chestnut soils (clay-illuvial oxigleyic agrozeems); (6) abandoned canal and road.

Carbonate-accumulative solonetzic and surface-calcareous agrozeems (Fig. 5b, soils 2) are located on the slopes of hollows, where soils undergo erosion, and on the watershed, where soils were truncated during the construction of the irrigation system and surface leveling. Their portion is 7.5%. Most of the soils of this group are deep-solonchakous, but solonchakous varieties also occur. The distribution pattern of these soils on the hollow slopes is asymmetric. They are mainly allocated to the right northern slope. This corresponds to the deviation of the temporary water flow on the hollow bottom of the east–west directed under the Coriolis force.

Concave positions on the watershed between and along the hollows are occupied by soils with the clay-illuvial BI horizon leached from carbonates. Most of them are nonsaline. Not deep depressions and hollows are occupied by clay-illuvial silty loamy agrozeems (meadow-chestnut soils) with a thin BI horizon. They comprise 19.8% of the total area (Fig. 5b, soils 3).

Bottoms of deeper hollows are occupied by agrodark-humus clay-illuvial soils and clay-illuvial nonsaline agrozeems with the depth of effervescence with HCl from 55 to 145 cm. They compose 3.5% of the total area (Fig. 5b, soils 4). There are not only medium, but also heavy loamy varieties among them.

In few places (1.3%), where hollows are crossed by linear objects (road and canal embankment), small areas of clay-illuvial solonchakous heavy and silty loamy agrozeems ((meadow-chestnut soils) are concentrated (Fig. 5b, soils 5).

Thus, the map compiled by identifying the main groups of soils, using the classification of satellite

images, presents the modern soil cover of the studied area of the Generalovskaya IS under post-irrigation conditions. Therefore, the method of catena determination of soil sampling sites during a terrain survey may be used in combination with remote sensing data and digital mapping techniques.

CONCLUSIONS

The 30-year-long operation of the Generalovskaya irrigation system resulted in significant changes in some soils of the Don River valley by the beginning of the 1990s. The condition of crops reflected in aerial photographs of that period pronouncedly varied from good to extremely depressed, depending on the initial salinity of soils – ingredients of chestnut–solonetz complexes and the formed regime of groundwater in irrigated areas. High groundwater level (<1.5 m) and increased mineralization (3–10 g/L) resulted in the formation of a solonchak of several tens of hectares in the area with secondary strongly saline soils around it.

Data of 2020 show that after the 25-year-long period without irrigation, the GWL became deeper than 5 m in the entire area of the former irrigated land, and secondary saline soils, including the secondary solonchak, underwent gradual desalinization. At the present time, slightly convex parts of the slope are occupied by deep-solonchakous and solonchakous, slightly saline, and solonetzic agrochestnut soils together with the carbonate-accumulative solonetzic agrozeems (plowed chestnut soils in C-1977). The bottoms of hollows and slightly concave surfaces are occupied by clay-illuvial nonsaline agrozeems (meadow-chestnut soils in C-1977).

In the areas, where the GWL was <3 m in the 1990s, evidences of secondary salinization in the form of calcium chlorides in soil solutions are now preserved.

The initial pattern of soils with different salt status was preserved on the four plots, but the salinity became lower. On the plot with generally good alfalfa status during irrigation, most of soils are now not saline to a depth of 2 m, and deep saline varieties are few. The plot with past spotty pattern of strong salinization now includes solonchakous and deep solonchakous soils with a relatively higher salt content. The area of the former solonchak still remains the most saline. It may be concluded that the modern salt status of soils is inherited from that of 25 years ago.

The combination of the catena method of performing soil sampling during terrain survey in accordance with remote sensing data, as well as digital mapping techniques provides the assessment of the presence or absence of carbonates close to the soil surface and of the depth of the first salt horizon. These data are necessary for elaboration and selection of optimal reclamation measures.

FUNDING

This work was performed within the framework of state assignments AAAA-A19-119081690030-0 “To Study the Effect of Natural Conditions and Land Use on the Soil Cover with the Participation of Saline, Solonetzic, and Vertic Soils” and FGUR-2022-0009 “To Study the Transformation, Evolution, and Degradation of the Soil Cover in Agricultural Landscapes at Different Organization Levels, Including Heterogeneity within Fields, Using a Combination of Terrain Surveys and Digital Technologies,” no. 122022800220-5.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

- G. I. Andreev, G. A. Kozlechkov, L. M. Rodionova, A. I. Semernikova, B. L. Gradusov, K. I. Fedorov, and N. P. Chizhikova, “Direction of soil formation in the Lower Don and Zapadnyi Manych areas and its change under irrigation,” in *Exploitation of Irrigation and Drainage Systems and Reclamation of Irrigated Lands in the North Caucasus*, Sb. Nauchn. Tr. Yuzhgiprovdokhoza XV (II), (Rostov-on-Don, 1973), pp. 255–307 [in Russian].
- I. N. Antipov-Karataev, *Reclamation of Solonchaks in the Soviet Union* (Izd. Akad. Nauk SSSR, Moscow, 1953) [in Russian].
- Basic Scales for Soil Morphology. Methodological Guidelines for Soil Description*. (Pochv. Inst. im. V.V. Dokuchaeva, Moscow, 1982), 58 pp. [in Russian].
- A. V. Baranovskaya and V. I. Azovtsev, “The impact of irrigation on the migration of carbonates in soils of the Volga region,” *Pochvovedenie* **10**, 17–26 (1981).
- S. Ya. Bezdina, *Quality of Irrigation Water. Principles and Methods of Assessment*. (ROMA, Moscow, 1997) [in Russian].
- I. N. Gorokhova, Extended Abstract of Candidate’s Dissertation in Technical Science (Moscow, 1992).
- I. N. Gorokhova, N. B. Khitrov, K. O. Prokop’eva, and V. A. Kharlanov, “Soil cover of the Svetloyarsk irrigation system after 50 years of reclamation practices// *Eurasian Soil Sci.* **51** (8), 1–11 (2018). <https://doi.org/10.1134/S1064229318060078>
- I. N. Gorokhova, I. N. Chursin, N. B. Khitrov, and E. I. Pankova, “Identification of agricultural lands on satellite images, in *Ecosystems: Ecol. Dynamics* **5** (3), 5–33 (2021) <https://doi.org/10.24412/2542-2006-2021-3-5-33>
- E. T. Degtyareva and A. N. Zhulidova, *Soils of Volgograd Oblast*. (Nizhne-Volzhscoe knizhn. Izd., Volgograd, 1970) [in Russian].
- E. B. Dedova, “Zonal scale for assessing irrigation water quality in the Kalmyk Republic,” *Sinergiya* **1**, 88–95 (2018). <https://vepi.ru/wp-content/uploads/2018/10/Sinergiya-2018-1.pdf>.
- F. R. Zaidel’man, “Ecological protection of reclaimed soils and agrolandscapes,” *Pochvovedenie* **1**, 5–12 (1993).
- B. A. Zimovets, *Ecology and Reclamation of Soils in the Dry Steppe Zone* (Pochv. Inst. im. V.V. Dokuchaeva, Moscow, 1991) [in Russian].
- E. V. Zinchenko, I. N. Gorokhova, N. G. Kruglyakova, and N. B. Khitrov, “Modern state of irrigated soils in the south of Privolzhskaya Upland,” *Byul. Pochv. Inst. im. V.V. Dokuchaeva*, **104**, 68–109 (2020). <https://doi.org/10.19047/0136-1694-2020-104-68-109>
- E. I. Ivanova, “Soils of the Southern Part of Podural’skoe Plateau and Adjacent Areas of the Caspian Lowland,” (Izd. Akad. Nauk SSSR, Leningrad, 1928) [in Russian].
- E. N. Ivanova and V. M. Fridland, “Soil complexes of dry steppes and their evolution,” in *Problems of the Amelioration of Forage Resources in Steppe, Semidesert, and Desert Zones of the USSR*. (Izd. Akad. Nauk SSSR, Moscow, 1954), pp. 162–190.
- Classification and Diagnostics of Soils of the Soviet Union* (Kolos, Moscow, 1977), p. 47 [in Russian].
- Classification and Diagnostic System of Russian Soils (Oikumena, Smolensk, 2004), 342 pp. [in Russian]
- V. A. Kovda, *Origin and Regime of Salt-Affected Soils* (Izd. Akad. Nauk SSSR, Moscow, 1946) [in Russian].
- V. A. Kovda, *Solonchaks and Solonchaks* (Izd. Akad. Nauk SSSR, Moscow, 1937) [in Russian].
- F. I. Kozlovskii, *Actual Natural and Anthropogenic Processes of Soil Evolution* (Nauka, Moscow, 1991) [in Russian].
- N. T. Kuznetsov and K. A. Solntsev, *Chemistry of Inorganic Hydrides*. (Nauka, Moscow, 1990) [in Russian].
- I. N. Lyubimova and E. T. Degtyareva, “Changes in the carbonate distribution in the soils of solonchakous com-

- plexes at agrogenic impact,” *Eurasian Soil Sci.* **33** (7), 746–751 (2000).
23. I. N. Lyubimova and A. F. Novikova, “Changes in the properties of solonchic soil complexes in the dry steppe zone under anthropogenic impacts,” *Eurasian Soil Sci.* **49** (5), 581–590 (2016).
<https://doi.org/10.7868/S0032180X16050129>
 24. N. G. Minashina, *Reclamation of Salt-Affected Soils*. (Kolos, Moscow, 1978) [in Russian].
 25. *Scientific Basics of Soil Degradation Control on Agricultural Lands of Russia and Formation of Soil Fertility Reproduction Systems in Landscape-Adaptive Farming. Vol. 1. Theoretical and Methodological Background of Soil Degradation Control on Agricultural Lands* (Pochv. Inst. im. V.V. Dokuchaeva, Moscow, 2013), 756 pp. [in Russian].
 26. *Field Guide on Correlation of Russian Soils* (Pochv. Inst. im. V.V. Dokuchaeva, Moscow, 2008), 182 pp. [in Russian].
 27. V. E. Prikhod’ko, *Irrigation of Steppe Soils: Functioning, Ecology, Productivity* (Intellect, Moscow, 1996) [in Russian].
 28. A. A. Rode and M. N. Pol’skii, “Soils of the Dzhanybek research station: morphology, mechanical and chemical compositions, and physical properties,” *Tr. Pochv. Inst. im. V.V. Dokuchaeva*, **56**, 3–214 (1961).
 29. N. B. Khitrov and A. A. Ponizovskii, *Manual on Laboratory Methods of the Study of Ionic-Salt Composition of Neutral and Alkaline Mineral Soils* (Pochv. Inst. im. V.V. Dokuchaeva, 1990) [in Russian].
 30. *Guidelines for Soil Description* (FAO, Rome, 2012) [in Russian].
 31. M. L. Sizemskaya, *Modern Natural-Anthropogenic Transformation of Soils in the North Caspian Semidesert* (KMK Press, Moscow, 2013) [in Russian].
 32. N. B. Khitrov and L. V. Rogovneva, “Five-year-long change in the salinity of soils and sediments on rice fields of the Karkinit Lowland after cessation of irrigation,” *Eurasian Soil Sci.* **54** (1), 135–149 (2021).
<https://doi.org/10.1134/S106422932101004X>
 33. V. N. Shchedrin, A. V. Kolganov, S. M. Vasil’ev, and A. A. Churaev, *Irrigation Systems of Russia: From Generation to Generation* (Gelikon, Novocheerkassk, 2013).
 34. IUSS Working Group WRB. *World Reference Base for Soil Resources 2014, Update 2015*. World Soil Resources Reports, no. 106 (FAO, Rome), 192 pp.
 35. *Guidelines for Soil Description*. 4th ed. (FAO, Rome, 2006).
 36. T. Khongnawang, E. Zare, P. Srihabun, and J. Triantafyllis, “Comparing electromagnetic induction instruments to map soil salinity in two-dimensional cross-sections along the Kham-Rean Canal using EM inversion software,” *Geoderma* **377**, 114611 (2020).
<https://doi.org/10.1016/j.geoderma.2020.114611>
 37. A. M. Paz, N. Castanheira, M. Farzamian, M. K. Paz, M. C. Goncalves, Santos F. A. Monteiro, and J. Triantafyllis, “Prediction of soil salinity and sodicity using electromagnetic conductivity imaging,” *Geoderma* **361**, 114086 (2020).
<https://doi.org/10.1016/j.geoderma.2019.114086>
 38. D. Ren, B. Wei, X. Xu, B. Engel, G. Li, Q. Huang, Y. Xiong, G. Huang, “Analyzing spatiotemporal characteristics of soil salinity in arid irrigated agro-ecosystems using integrated approaches,” *Geoderma* **356**, 113935 (2019).
<https://doi.org/10.1016/j.geoderma.2019.113935>
 39. R. Taghizadeh-Mehrjardi, K. Schmidt, N. Toomanian, B. Heung, T. Behrens, A. Mosavi, S. S. Band, A. Amirian-Chakan, A. Fathabadi, and T. Scholten, “Improving the spatial prediction of soil salinity in arid regions using wavelet transformation and support vector regression models,” *Geoderma* **383**, 114793 (2021).
<https://doi.org/10.1016/j.geoderma.2020.114793>
 40. F. Tian, M. Hou, Y. Qiu, T. Zhang, Y. Yuan, “Salinity stress effects on transpiration and plant growth under different salinity soil levels based on thermal infrared remote (TIR) technique,” *Geoderma* **357**, 113961 (2020).
<https://doi.org/10.1016/j.geoderma.2019.113961>
 41. F. Wang, Z. Shi, A. Biswas, S. Yang, J. Ding, “Multi-algorithm comparison for predicting soil salinity,” *Geoderma* **365**, 114211 (2020).
<https://doi.org/10.1016/j.geoderma.2020.114211>
 42. J. Wang, J. Ding, D. Yu, X. Ma, Z. Zhang, X. Ge, D. Teng, et al., “Capability of Sentinel-2 MSI data for monitoring and mapping of soil salinity in dry and wet seasons in the Ebinur Lake region, Xinjiang, China,” *Geoderma* **353**, 172–187 (2019).
<https://doi.org/10.1016/j.geoderma.2019.06.040>
 43. E. Zarea, M. Arshad, D. Zhao, G. Nachimuthu, J. Triantafyllis, “Two-dimensional time-lapse imaging of soil wetting and drying cycle using EM38 data across a flood irrigation cotton field,” *Agric. Water Managem.* **241**, 106383 (2020).
<https://doi.org/10.1016/j.agwat.2020.106383>

Translated by I. Bel’chenko