ISSN 1064-2293, Eurasian Soil Science, 2009, Vol. 42, No. 13, pp. 1479–1486. © Pleiades Publishing, Ltd., 2009.

SOIL CHEMISTRY

Salinization Dynamics in Irrigated Soils of the Svetloyarsk Irrigation System, Volgograd Oblast

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Received May 29, 2008

Abstract—On the basis of soil surveys performed by the Volgograd hydrogeological reclamation expedition in 1998 and 2006, published data, and original materials obtained by the authors, the dynamics of soil salinization within the Svetloyarsk irrigation system in Volgograd oblast during the irrigation and post-irrigation periods have been traced. It is found that high irrigation rates under conditions of poor drainage and closed drainage basins upon both shallow (within the Caspian Lowland) and relatively deep (on the Ergeni Upland) occurrence of saline groundwater and the presence of natural salts in the soils and subsoils lead to the rise in the groundwater level above the critical level and the development of secondary salinization in the previously surface-saline, deeply saline, and even nonsaline soils. During the post-irrigation period (15–18 years) under modern climatic conditions, the groundwater level has been descending to a depth of more than 3 m, and the degree of salinity in the upper meter of light chestnut and meadow-chestnut soils has decreased owing to the leaching of salts with atmospheric precipitation.

DOI: 10.1134/S1064229309130080

INTRODUCTION

Secondary soil salinization is the major of negative processes developing upon soil irrigation in arid and semiarid regions [8]. The most active construction of irrigation systems (ISs) in Volgograd oblast took place at the end of the 1980s, when 345 200 ha were irrigated, including 152 800 ha within the ISs proper (overall, 16 ISs were created in this oblast) [11]. Within a larger part of these systems, a considerable rise in the groundwater table took place, and the soils were subjected to secondary salinization, alkalization, and waterlogging [5–7, 11, 12].

Since the 1990s, many irrigated lands in Volgograd oblast, as well as in the entire Russia, have been abandoned or converted to rainfed farming. In 2006, the area of irrigated lands in Volgograd oblast reached 195 600 ha, including 111 800 ha within the ISs [7]. The state of formerly irrigated soils after the cessation of irrigation remains poorly studied.

The aim of our work was to estimate the salt status of formerly irrigated soils and to trace the dynamics of soil salinization within the Svetloyarsk IS and, particularly, within the key plot Chervlenoe for a period from 1988 to 2006. The materials of soil and hydroreclamation surveys performed by the Volgograd hydrogeological reclamation expedition[1] [9], the materials published by Gorokhova [2], and the results of our original investigations performed in this area in 1998 and 2007.

[1] The authors are thankful to the workers of this expedition for the kindly provided possibility to use them in our study.

OBJECTS AND METHODS

Soils of the Svetloyarsk IS were studied. This system was built in 1962 (Fig. 1a). It is found in the arid agroclimatic zone with the aridity factor of 3.0. Annual precipitation varies from 220 to 300 mm. This system is found in two different geomorphic regions. A larger eastern part of the system (irrigation plots Svetloyarsk, Raigorod, Krasnoarmeisk, Dubovoovrazhnyi, and Tsatsinsk (nos. 1–5)) lies within the Kvalyn clayey plain and Sarpa Hollow belonging to the Caspian Lowland. This area is characterized by them most unfavorable irrigation conditions because of the lack of natural drainage and shallow (5–10 m on the average; 0–3 m within the Sarpa hollow) occurrence of saline (5–20 mg/l) groundwater [3, 10, 11]. Before irrigation, various hydromorphic and semihydromorphic soils (meadow, meadow-chestnut, and meadow-bog soil) in combinations with semihydromorphic and hydromorphic solonetzes occupying up to 50% of the area predominated in the soil cover of this region. The soils had the sulfate–chloride and chloride types of salinization. Elevated positions within the Khvalyn Plain were characterized by a predominance of the complexes of solonetzic light chestnut soils with automorphic solonetzes of the sulfate–chloride and chloride–sulfate types of soil salinization [2, 3, 10].

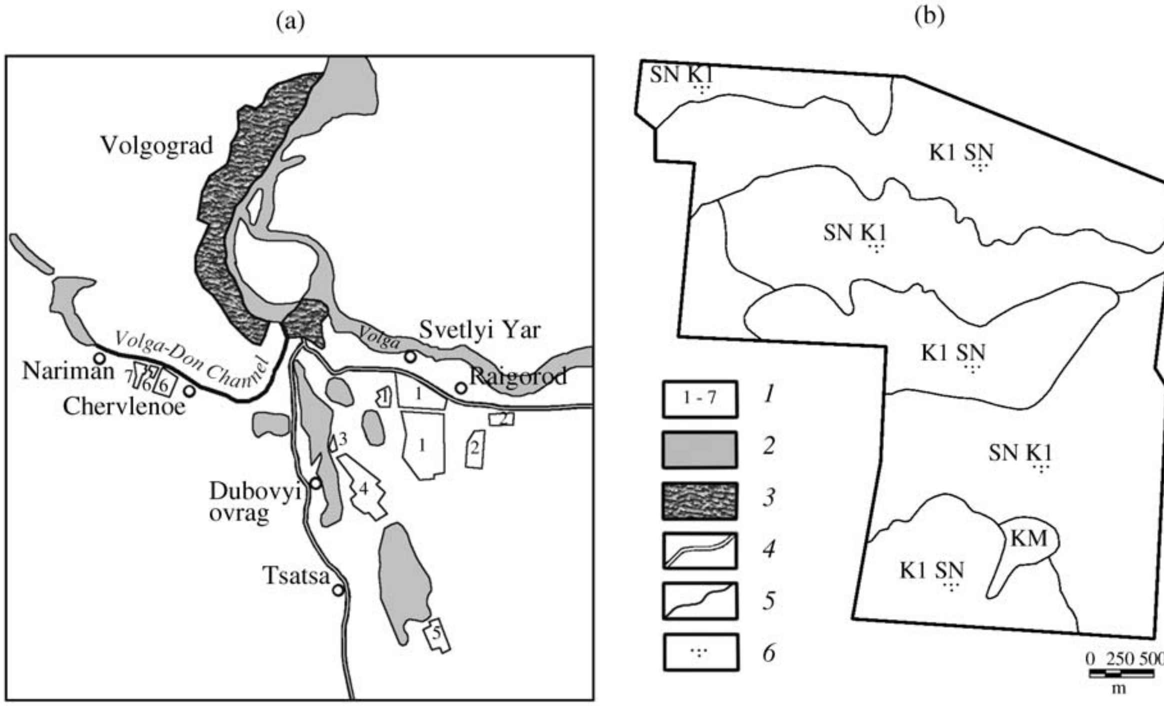

Fig. 1. Location of the particular irrigation plots within the Svetloyarsk IS (a) and the soil map of the Chervlenoe plot compiled before the irrigation system construction in 1962 (b). Conventional signs: (*1*) irrigation plots (massifs) (1—Svetloyarsk, 2—Raigorod, 3—Krasnoarmeiskii, 4—Duboovrazhnyi, 5—Tsatsinsk, 6—Chervlenoe, and 7—Tingutinskii); (*2*) the Volga River, water reserves, and ponds; (*3*) residential area of Volgograd; (*4*) roads; (*5*) boundaries of soil delineations; and (*6*) percent of accompanying soil in the soil polygon reaches 25–50%. Soils: SN, solonetzes; K1, light chestnut; and KM, meadow-chestnut soils.

A smaller western part of the Svetloyarsk IS occupies eastern outliers of the Northern Ergeni Upland. This elevated area is composed of saline calcareous loesslike loams and clays with a thickness of 2–3 to 10 m The absolute heights of the local watersheds reach 100–104 m a.s.l. The groundwater table before the beginning of irrigation was found at a depth of 15–30 m within the local elevations and 5–10 m within the local depressions. The groundwater salinity varied from 1–3 to 5–15 g/l. The low intensity of the groundwater discharge in the entire area should be mentioned. Two plots of the IS—Chervlenoe and Tingutinskii—were allocated to this geomorphic region. The soil cover of the Northern Ergeni Upland before irrigation consisted of the complexes of light chestnut soils (often, with solonetzic features) and solonetzes proper that occupied from 25 to 50 or more than 50% of the area of the complexes.

Sodium, sulfate, and chloride ions predominated in the composition of salts. The presence of soda was noted for the solonetzes developing on the Ergeni Upland and within the Sarpa Hollow and the Khvalyn Plain.

On the plot Chervlenoe (with a total area of 1736 ha), 43 boreholes to a depth of 3 m were drilled in 1988 and 40 boreholes to the same depth were drilled in 2006. Core samples were taken from the depths of 0–10, 10–30, 30–50, 50–70, 70–100, 100–150, 150–200, 200–250, and 250–300 cm. In the water extracts (1 : 5) from these samples, the concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^-, Cl^-, and SO_4^{2-} were determine by standard methods [1]. The degree of salinization in the irrigated and formerly irrigated soils was judged from the weighted average content of toxic salts in the upper soil meter according to the criteria suggested in the monograph on salt-affected soils of Russia [4].

RESULTS AND DISCUSSION

1. Soil salinization dynamics within the Svetloyarsk IS. The rise in the groundwater level at some of the irrigated plots was observed at the beginning of exploitation of this IS in the 1960s. Despite the use of irrigation water of sufficiently good quality (with the salt content of less than 0.5–0.6 g/l) from the Volga River, the secondary salinization of irrigated soils took place. It was provoked not only by the unfavorable soil reclamation conditions (the natural salinity of soils and parent materials) but also by the certain drawbacks in the design of the IS, which was not supplied with the drainage network under conditions of the poor natural

Table 1. Areas of irrigated soils with different depths and salinities of groundwater at the Svetloyarsk IS in 1989, 2001, and 2007, ha (according to [7])

Year	Total area of irrigated soils	Distribution of irrigated soils								
		by the groundwater level, m						by the groundwater salinity, g/l		
		<1.0	1.0–1.5	1.5–2.0	2.0–3.0	3.0–5.0	>5.0	<1.0	1.0–1.5	>3.0
1989	7065	4	274	474	961	3732	1620	400	2722	3943
2001	7264	–	24	193	646	3624	2777	1012	2329	3923
2007	6432	–	–	–	–	1943	4489	892	1967	3573

Note: Hereinafter, dashes denote that the soils of given categories have not been identified.

Table 2. Areas of saline soils at the Svetloyarsk IS in 1989, 2001, and 2007, ha (according to [7])

Year	Total area of irrigated soils	Soil salinization in the layer of 0–100 cm							
		slight		moderate		strong		total	
		1	2	1	2	1	2	1	2
1989	7065	1121	210	628	784	66	86	1815	1080
2001	7264	977	–	893	235	–	96	1870	331
2007	6432	1623	–	490	85	30	94	2143	179

Note: (1) natural salt-affected soils and (2) soils subjected to secondary salinization.

drainage of irrigated lands. Up to the 1970s, furrow irrigation and check irrigation were practiced. Irrigated fields were used for growing vegetable and fodder crops with high demands for the water supply. High duties of irrigation water were applied. As a result, in 1989, the groundwater rise to a depth of less than 3 m was observed on about 25% of the irrigated territory (Table 1). Salt-affected soils occupied more than 40% of this territory. Secondary saline soils comprised two thirds of their area. In most cases, the degree of soil salinity was low and moderate.

According to official data of land cadaster, the area of irrigated lands in 2001 was approximately the same as that in 1989. It should be noted that irrigated lands in cadaster reports take into account all the lands, where ISs are preserved irrespectively of their real functioning. In fact, more than 70% of soils within the Svetloyarsk IS were no more irrigated in 2001. On the irrigated plots, irrigation was irregular, and net duties of water were lower. By 2001, a decrease in the groundwater level was observed. The area of soils with the groundwater depth of less than 3 m decreased by two times. The groundwater salinity remained at the previous level (Table 1). The area of secondary-saline soils decreased twofold (Table 2).

In 2007, the irrigated area comprised 6432 ha, i.e., it decreased by 11% in comparison with 2001. In fact, irrigation was not performed on 90–95% of the formally irrigated area. This situation favored the further decrease in the groundwater level. Soils with the groundwater at a depth of more than 5 m occupied 70% of the IS area; on the remaining area, the groundwater depth was from 3 to 5 m (Table 1). There were not plots with the critical (<3 m) depth of the groundwater. An increased salinity of the groundwater was preserved. The area of secondary saline soils decreased, and the naturally saline soils (predominantly, solonetzes) preserved their salinity (Table 2).

2. Soil salinization dynamics at the Chervlenoe plot of the Svetloyarsk IS. The analysis of soil salinization dynamics within the Svetloyarsk IS is mainly based on cadaster assessments of the state of irrigated lands in Volgograd oblast made in 1989, 2001, and 2007 [7]. For a moder adequate assessment of the processes taking place in the formerly irrigated soils after the cessation of irrigation, let us analyze the results of special surveys of the Chervlenoe plot performed by Gorokhova in 1988 [2], the Volgograd hydrogeological reclamation expedition in 1998 and 2006 [9], and by the authors of this paper (in 1998 and 2007). This plot is found on the northern slope of the Ergeni Upland

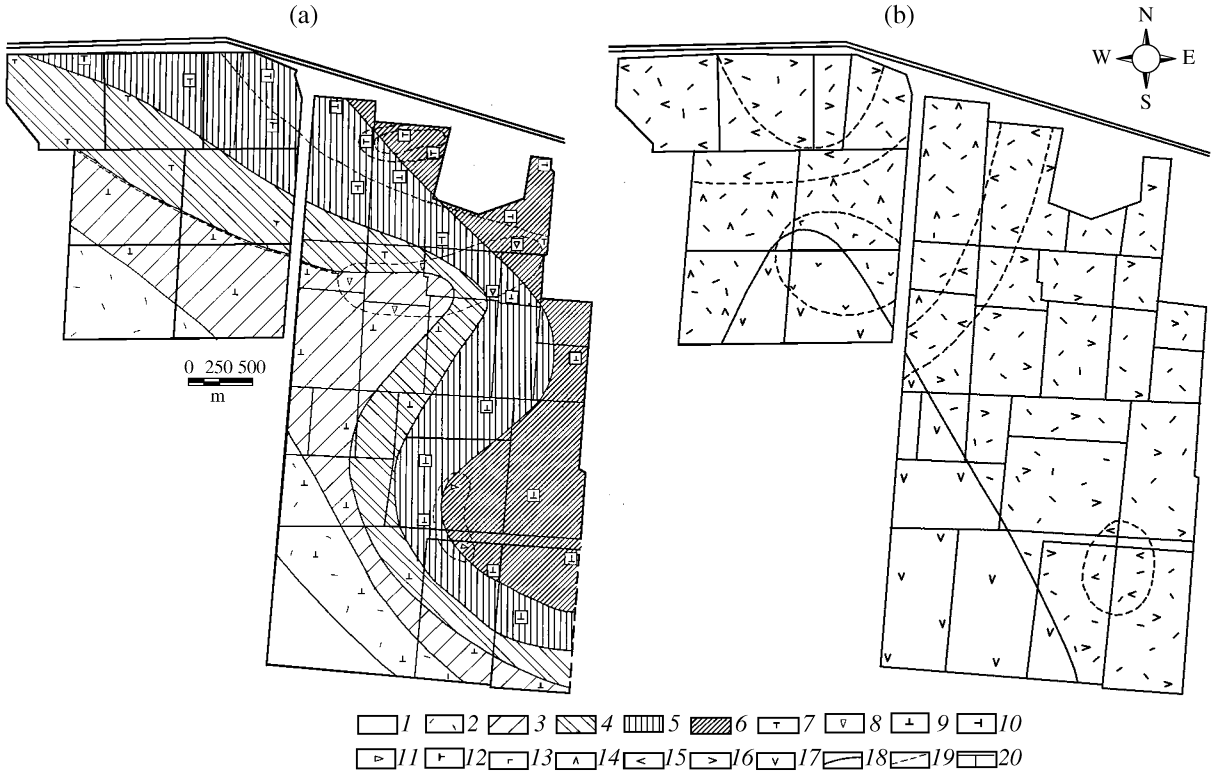

Fig. 2. Maps of the depth, salt content, and salt chemistry of the groundwater in (a) 1988 and (b) 2006. Groundwater level, m (*1*) >5, (*2*) 3–5, (*3*) 2.5–3.0, (*4*) 2.0–2.5, (*5*) 1.5–2.0, and (*6*) 1.0–1.5. Salt content (g/l) and the chemistry of predominant salts: (*7*) 5–10, chloride–sodium—magnesium; (*8*) 5–10, sulfate–sodium; (*9*) 5–10, chloride–sodium; (*10*) 3–5, chloride–sodium; (*11*) 3–5, sulfate–calcium; (*12*) <1, chloride–sodium; (*13*) <1; (*14*) 1–3; (*15*) 3–5; (*16*) 5–10; (*17*) >10. Boundaries: (*18*) delineations with different depths of the groundwater level, (*19*) delineations with different salt contents in the groundwater, and (*20*) particular fields.

with absolute heights of 97–102 m and borders the Volga–Don canal (Fig. 1). Gentle slopes predominate in the relief. The groundwater depth before irrigation varied from 18–20 to 5 m. The groundwater salinity varied from 1 to 10 g/l.

The complexes of solonetzic light chestnut soils and solonetzes (25–50 and >50%, respectively) with a small percentage of meadow-chestnut soils predominated in this area (Fig. 1b). The virgin solonetzic light chestnut soils were slightly or moderately saline in the layer deeper than 50–100 cm with a predominance of sulfate–chloride–sodium or chloride–sulfate–sodium salinization; often, with participation of soda in the solonetzic horizon. In the deep (> 1 m) soil layer, the chloride–sulfate–sodium salinization predominated.

By 1988, a considerable rise in the groundwater level took place at this irrigation plot [2, 9]. The critical depth (<3 m) of the groundwater was observed within the entire area (Fig. 2a). In the northern and eastern parts of the plot with somewhat lower absolute heights, the groundwater was found at a depth of 1–2 m. The groundwater salinity in the northern part reached 5–10 g/l with a predominance of sodium and magnesium chlorides; in some places, the groundwater of the chloride–sodium type with the salt content of 1–5 g/l was present. In the eastern part of the plot, the groundwater of that type with the salt content of 5–10 g/l predominated. Within the remaining part of the irrigation plot, the groundwater level varied from 2.5 to 5 m, and the salt content reached 5–10 g/l with a predominance of sodium chlorides.

The rise in the groundwater level led to the widespread development of soil salinization (Fig. 3a). Before irrigation, soils containing salts in the upper meter (predominantly, solonetzic soils) comprised 25–50 and 50–75% of the area of soil complexes in different parts of the plot. In 1988, salinization in the upper meter was also developed in the formerly deeply and potentially saline light chestnut soils and in the nonsaline meadow-chestnut soils. The strong and very strong secondary salinization was observed on 40% of the area in the northern and northeastern part of the Chervlenoe plot, where the groundwater depth varied from 1 to 2.5 m. The moderate degree of soil salinization in the upper meter was typical of the soils in the central and eastern parts of the irrigation plot, where the groundwater depth varied within 1–3 m. On the remaining territory, only slight secondary salinization in the upper soil

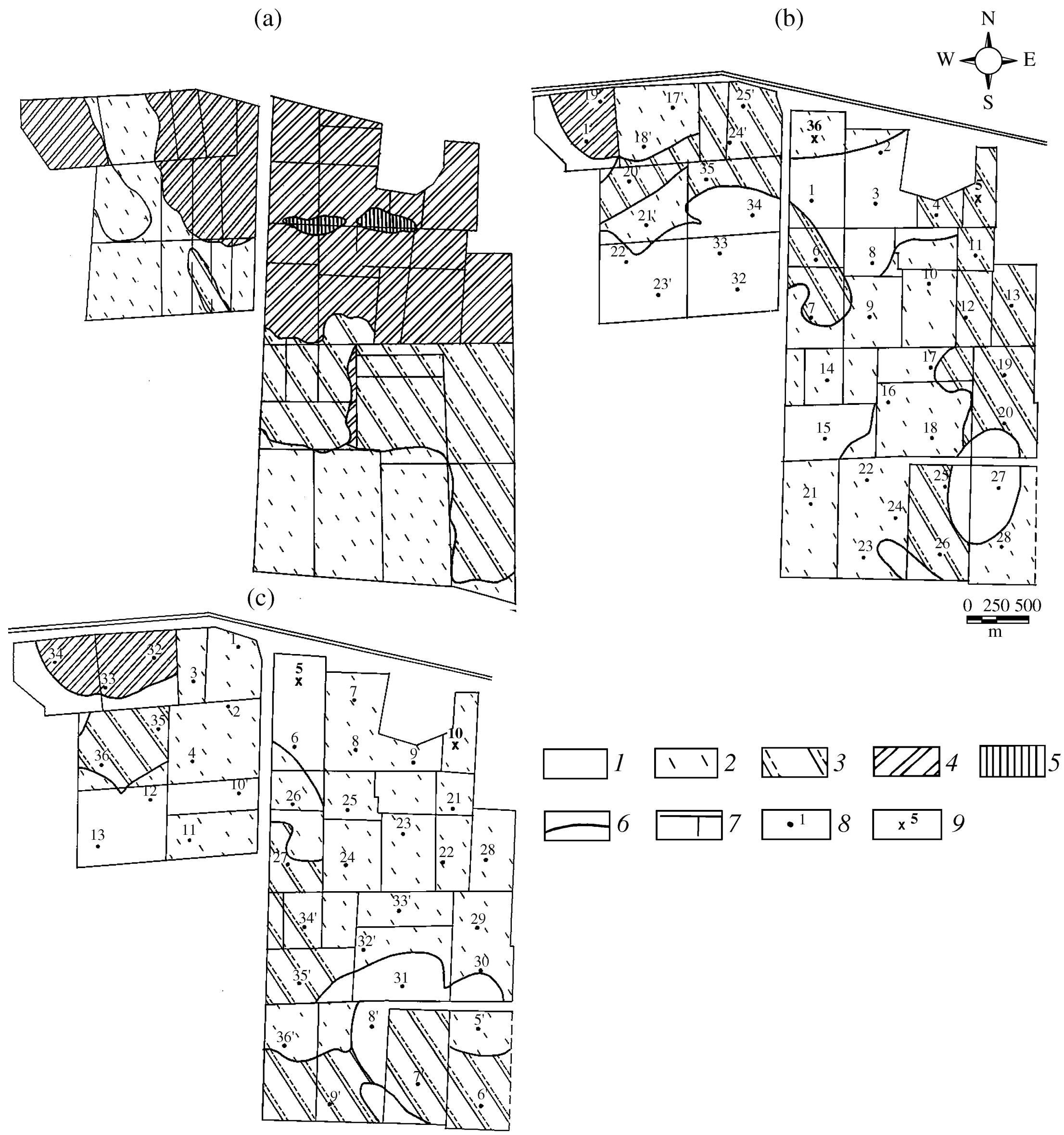

Fig. 3. Maps of the degree of soil salinization in (a) 1988 and (b) 2006. Soils: (*1*) nonsaline, (*2*) slightly saline, (*3*) moderately saline, (*4*) strongly saline, (*5*) very strongly saline; (*6*) boundaries of soil salinization delineations; (*7*) boundaries of particular fields; (*8*) borehole numbers; and (*9*) boreholes, the distribution of salts in which is presented in Fig. 4.

meter was identified; the groundwater table was at a depth of 2.5–5.0 m.

In the 1990s, irrigation was stopped on a larger part of the Chervlenoe plot. It was used for rainfed growing of salt-tolerant crops (sorghum, Sudan grass, barley) with annual soil cultivation and special water-retention measures. We do not have direct data on the groundwater level at this plot for this period. However, judging from the results of the groundwater survey within the Svetloyarsk IS in 2001 (Table 1), we can suppose that some decrease in the groundwater level took part in the later 1990s.

The salt survey of the Chervlenoe plot was performed in 1998, 7–8 years after the cessation of irrigation (Fig. 3b). By this time, the soil salinity on the plot decreased considerably. Strongly saline soils that existed in 1988 turned into slightly and moderately saline soils. Strongly saline soils were only preserved in the northwestern part of the plot. These soils contained 0.4–0.9% of toxic salts (with the sulfate–chloride–sodium type of salinity) in the upper meter. In the moderately saline soils, the content of toxic salts in the upper meter was 0.25–0.50% (sulfate–chloride or chloride–sulfate salinization predominated). In the slightly saline soils, the content of toxic salts in the upper meter was 0.1–0.2%; sulfate or chloride–sulfate salinization predominated. In the layer of 1–3 m, the content of toxic salts in the slightly and moderately saline soils increased up to 0.8% and chlorides predominated among them.

Our studies performed on this plot in 1998 [11] demonstrated that strongly saline soils were mainly represented by agrosolonetzes. Often, these soils contained small amounts of sodium chloride in the upper 25 cm. The layer of 25–80 (100) cm contained up to 1.1–1.2% of toxic salts with a predominance of sulfates and chlorides. The exchangeable sodium percentage in the plow layer reached 12% of the CEC. Moderately saline soils were represented by light chestnut soils. These soils contained toxic salts (predominantly sodium sulfates and chlorides) in amounts of about 0.3% in the upper meter and about 0.15% in the upper 30 cm. In the deeper layers (>1 m) the content of toxic salts in the moderately saline soils was 0.3–0.35%. In the slightly saline soils, the salt content in the layer of 30–150 cm was 0.1–0.2%. The exchangeable sodium percentage was low.

Thus, the cessation of irrigation on a larger (70%) part of this plot and irregular irrigation with small duties of water on the remaining territory favored the decrease in the groundwater lover and the transformation of soil salinity patterns. Strongly saline soils were transformed into moderately, slightly, and nonsaline soils. These changes were especially pronounced for the secondary-saline light chestnut soils. Some decrease in the salinity of solonetzes also took place, though most of them belonged to the group of strongly saline soils.

Since 1998, the plot has not been irrigated. By 2006, the groundwater level decreased considerably (Fig. 2b). Within a larger part of the plot, the groundwater was found deeper than at 5 m; on the remaining territory, it was found at a depth of 3–5 m. In the deeply (>5 m) lying groundwater, the salt content exceeded 10 g/l, i.e., it increased in comparison with that in 1998. In the areas with the groundwater level of 3–5 m, the salt content also often exceeded 10 g/l; in some places, it varied from 5 to 10 g/l. It is probable that the increase in the groundwater salinity was due to the leaching of soluble salts from the upper horizons of salt-affected soils, or due to the absence of the additional diluting effect of irrigation water.

The soil survey performed in 2006 demonstrated the transformation of moderately and slightly saline soils (according to the survey data of 1998) into slightly saline and nonsaline soils (Fig. 3c). Strongly saline soils were only preserved on a relatively small area in the northwestern part of the plot with the high salinity (5–10 g/l) of moderately deep (3–5 m) groundwater.

At the same time, there were areas, where the previous degree of soil salinity (slight or moderate) was preserved, or where the soil salinity increased from slight to moderate values. These facts point to the active migration of salts in the upper soil meter in dependence on the soil moistening and drying conditions; the high spatial variability of soil salinization should be noted.

The transformation of moderately saline soils (1998) into slightly saline soils (2006) can be judged from the salt profiles shown on Figs. 4a and 4b. The boreholes, from which the corresponding samples were taken in 1998 and 2006, were located in the same place. It is seen from the curves that the salt maximum at the depth of 100 cm (1998) was displaced to the depth of 200 cm in 2006 owing to leaching of readily soluble sodium sulfates and chlorides; owing to this, the sulfate–chloride–sodium type of salinization in the upper 50 cm was replaced by the sulfate–sodium–calcium salinization. The content of toxic salts in the upper soil meter decreased from 0.05–0.54% in 1998 to 0.05–0.15% in 2006. In the deeper layer (> 1.5 m), the content of toxic salts increased from 0.3–0.4 to 0.9%, respectively.

The transformation of a slightly saline soil in 1998 into nonsaline soil in 2006 is displayed in Figs. 4c and 4d. Sodium sulfates and chlorides were leached off from the upper soil meter and accumulated in the lower horizons, particularly in the layer of 100–150 cm. The content of toxic salts in this layer varied from 0.04 to 0.16% in 1998 and from 0.07 to 0.3% in 2006.

The changes in the salt status of secondary saline soils during the post-irrigation period of their developed are clearly seen upon their comparison with the salt distribution in the naturally saline virgin solonetz (Fig. 4e). The slight chloride–sulfate salinization in the upper 40 cm of this soil (with the total content of toxic salts of 0.1–0.2%) is replaced by the moderate and strong salinization in the deeper horizons with a maximum (1.6%) at a depth of 70 cm. Such distribution of salts is typical of the solonetzes in the northern Ergeni area.

CONCLUSIONS

The regular dynamics of salinization–desalinization processes has been traced for the irrigated soils of the Svetloyarsk IS during the irrigational and post-irrigational periods.

Irrigation with water of good quality (0.5–0.6 g/l) taken from the Volga River started in 1962. By the end of the 1980s, the widespread development of secondary saline soils was noted for the irrigated area according to cadaster assessments [7]. This was obviously due to the rise in the level of saline groundwater. The area of secondary-saline soils reached 50% of the total area of saline soils. Along with naturally saline solonetzes, salinization processes affected also deeply and poten-

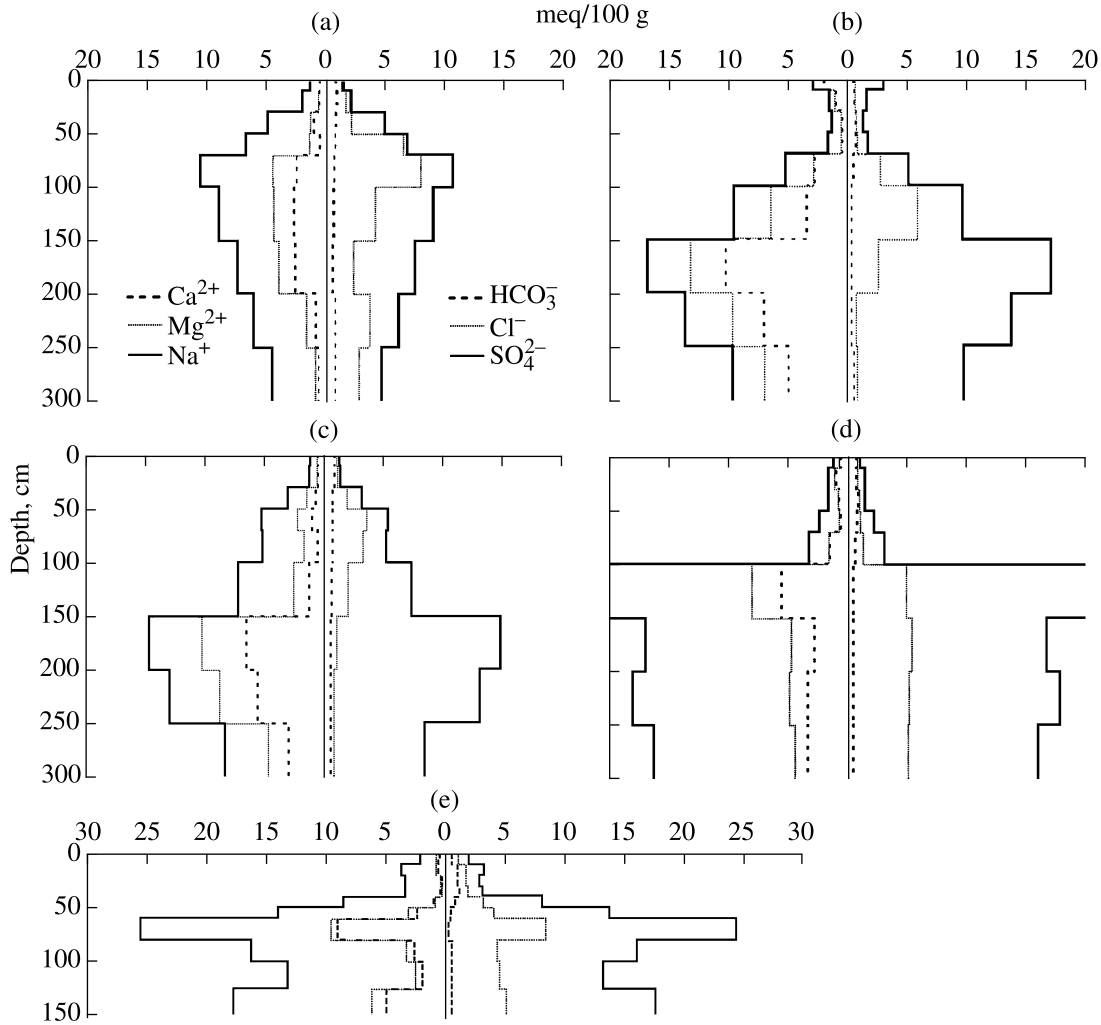

Fig. 4. Salt distribution profiles in the anthropogenically transformed solonetzes from (a) borehole 5 (1998), (b) borehole 10 (2006), (c) borehole 36 (1998), and (d) borehole 5 (2006); (e) virgin solonetz (2006). The location of the boreholes is indicated in Figs. 3b and 3c.

tially saline light chestnut soils and nonsaline meadow-chestnut soils.

After the cessation of irrigation in the 1990s, the area of secondary-saline soils decreased owing to a general decrease in the groundwater depth below the critical limit (3 m). By 2007, the area of secondary-saline soils decreased by six times in comparison with that in 1989. The areas of naturally saline soils (predominantly, solonetzes) did not change much during the studied period, which points to the preservation of soil salinity in solonetzes.

At the Chervlenoe plot of the Svetloyarsk IS, the rise in the groundwater level led to a significant increase in the areas of salt-affected soils. The secondary salinization manifested itself for the areas with formerly nonsaline or potentially saline light chestnut and nonsaline meadow-chestnut soils that compose from 25 to 75% of the total plot area. During the post irrigation period in the 1990s and early 2000s (up to 2007), the groundwater level decreased by 2–3 m, which was accompanied by desalinization in the upper soil meter and some accumulation of sodium sulfates and chlorides in the lower horizons (1–2 m).

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research (project no. 06-04-39022a) and the National Natural Science Foundation of China (project no. 40711120200).

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