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GENESIS AND GEOGRAPHY OF SOILS

Morphological and Chemical Properties of Soils on the Eastern Shore of Lake Bulukhta, Northern Caspian Region

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Abstract—Morphological and chemical properties of soils in a soil catena crossing the eastern coast of salt Bulukhta Lake in the northern part of the Caspian region were studied. The catena included different kinds of solonetzes and solonchaks occupying the lake bottom. The morphogenetic and analytical study of the soils made it possible to judge the intensity of the major soil-forming processes on different elements of the local topography. It was shown that the intensity of humus accumulation increases from the autonomous eluvial positions towards the accumulative positions and decreases in the superaqual landscape, where the accumulation of organic matter is limited by the high soil salinity and by the washout of humified material from the shore into the lake. In the transitional and accumulative positions of the catena with saline parent materials, the upper soil horizons are subjected to desalinization owing to the additional water inflow and transformation of surface runoff into subsurface water flows along zoogenic pores. A comparative analysis of the seasonal dynamics of the level, salinity, and chemical composition of groundwater under the soils of the catena was performed. It demonstrated that the dynamics of the groundwater level and salinity in the geochemically subordinate positions depend on the hydrological regime of the lake, which, in turn, is controlled by the amount and seasonal distribution of precipitation.

Keywords: saline soils, solonetzes, catena, lacustrine landscapes, dynamics of groundwater level and salinity, Caspian Sea region

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INTRODUCTION

Interest in the study of lacustrine ecosystems is related to their high vulnerability under conditions of enhanced anthropogenic loads and climatic changes. Salt lakes are widespread in the northern Caspian region. Lake Bulukhta is a typical drying lake under arid climate conditions. The unique and poorly studied ecosystems of its shores are of great interest. The endemic communities of tamarisk (*Tamarix laxa* Willd.) are still preserved at the northern boundary of their area. These communities are the ecological relicts of the psammophytic and meadow stages of plant succession during the overgrowth on the coasts of the Caspian Sea [11]. They serve as habitats of rare animal species, so their destruction leads to a considerable reduction of both plant and animal diversity of the area [19]. Brushwood communities on the shores of the lake enhance erosion resistance of coastal slopes, which is particularly important for Lake Bulukhta, which has a highly dynami water regime [6–8]. In turn, the dynami water regime of the lake affects the state of surrounding ecosystems and the character of soil-forming processes in the coastal landscapes [21, 28]. The soil cover near Lake Bulukhta is insufficiently studied; few data are available on the properties of soils, parent materials, and groundwater in this area [16]. In this context, the aim of our study was to characterize the genetic features of soils in the landscapes on the eastern coast of Lake Bulukhta.

The particular goals included (a) the study of morphological and chemical properties of soils on different elements of topography, (b) the identification of the main elementary soil-forming processes (ESPs) and the degree of their development in different parts of the catena, and (c) the determination of the chemical composition and salinity of the groundwater and their relationships with the soil salinity.

OBJECTS AND METHODS

Lake Bulukhta is found in the western part of the Trans-Volga area of the Caspian Lowland belonging to the marine accumulative plain of the Khvalyn Age. This territory represents a combination of flats dissected by occasional dry valleys and flat-bottomed ravines (balkas) and vast depressions occupied by Bulukhta, Elton, and Botkul salt lakes. The plain is elevated at about 20–25 m above sea level, and the absolute heights of the water level in the lakes vary from +16 m (Lake Bulukhta Lake) to –16 m (Lake Elton). The climate is extremely arid. The potential evaporation reaches 1000 mm, while the mean annual precipitation does not exceed 300 mm [12].

The depression of Lake Bulukhta is of the residual erosional origin [16]. Its coastline is slightly dissected by shallow balkas and karsts and surface subsidence microdepressions. The lake is not deep, and its catchment is relatively large. Water fills the lake after the snowmelt season; by the beginning of summer, its larger part is transformed into a wet solonchak with only a small area of open water. The water level in the lake does not reach its maximum every year and depends on winter precipitation and the conditions of snow melting in spring. During the snowmelt season, the water in the lake becomes considerably fresher [25].

Water and chemical regimes of the lake are highly variable. Water salinity varies from 19 to 200‰ with a predominance of NaCl (from 51% in the fall to 56% in the early summer). The second place belongs to Na_2SO_4 (24.1–38.1%). A significant part of salts in the lake water is represented by $MgSO_4$ (up to 18.6% in summer) and $CaSO_4$ (up to 7.2% in spring) [25].

The shoreline of the lake is shown in the maps by the contour line of 16.7 m. The first modern terrace (18.5 m) is separated from the shore by the 0.5- to 1.8-m-high cliff. It passes close to the water surface of the lake and is eroded by the surf when the lake depression is filled with water.

With respect to the botanical-geographical zoning, Lake Bulukhta and the adjacent area are assigned to the transitional zone between the xerophytic shrub Northern-Turan (Caspian) deserts with a predominance of halophytic species (*Atriplex cana* C.A. Mey, *Limonium suffruticosum* (L.) O. Kuntze, *Halimione verrucifera* (Bieb.) Aellen, and *Halocnemum strobilaceum* (Pall.) Bieb) and dwarf shrub–bunchgrass desert-steppes [28].

Field studies were performed in 2012–2013. We studied a soil catena on the eastern coast of Lake Bulukhta. The catena crossed the first terrace with a well-pronounced coastal cliff and the bottom of the lake depression. It was 280 m in length; the amplitude of heights reached 4 m, including the 1-m-high coastal cliff.

Soil pits were set in agreement with the observed changes in the plant cover and topography (figure). Detailed descriptions of soil morphology were made, and the soil samples were taken from the genetic horizons. Laboratory determinations included the contents of organic matter, carbonates, and gypsum; the pH of water extract (1 : 2.5); the composition of exchangeable cations; and the composition of soil water (1 : 5) extracts. Boreholes were drilled to the groundwater table near the soil pits. The groundwater level, mineralization, and chemical composition were measured in the boreholes for two seasons.

The analyses of groundwater and soil water extracts were made by routine methods [9]; the content of SO_4^{2-} in the water extracts was determined according to the method of Komarovskii [10]. The content of Na^+ in the water extract was calculated as the difference between the sum of anions and the sum of Ca^{2+} and Mg^{2+}. We also determined the exchangeable cations by the Pfeffer method modified by Molodtsova and Ignatova [9], soil carbonates by the method of Kozlovskii, the total content of sulfate ions by the gravimetric method in modification by Khitrov [23], and the organic matter content according to the wet combustion method of Tyurin. Soil salinization was evaluated according to the criteria given in [13]. The classification position of the studied soils and the symbols of soil horizons were given according to the *Field Guide on Russian Soils* [22].

RESULTS AND DISCUSSION

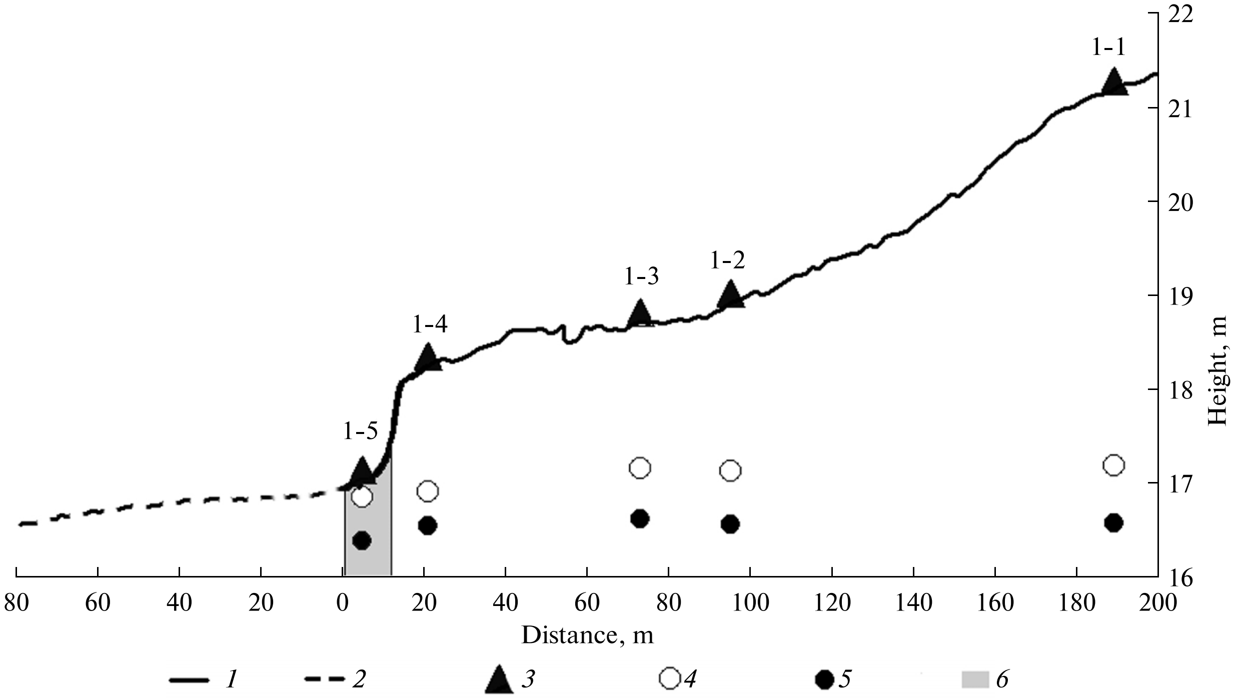
The most elevated eluvial positions of the catena (on the surface of the second lake terrace) are occupied by the light solonchakous solonetzes (pit 1-1) under grass–*Kochia–Tanacetum–Artemisia* communities. The transitional positions on the gentle slope of the second terrace are occupied by the light slightly solonchakous solonetzes (pit 1-2) under grass–*Artemisia* communities with participation of *Halimione verrucifera* and *Limonium* and by light-humus medium deep deeply solonchakous solonetzes (pit 1-3) under grass communities with *Artemisia*. In the accumulative positions of the first terrace, light-humus thin solonchakous quasi-gley solonetzes are developed under forb–halophyte-dwarf shrub communities with *Halocnemum strobilaceum* (pit 1-4). In the superaqual position near the shore (on the bottom of the lake), humus-stratified gleyed solonchaks are developed under *Tamarix laxa* Willd communities (pit 1-5). Somewhat apart from the catena, on the lower part of the slope of the second terrace and on the first terrace, microdepressions of up to 10 m in diameter and 70 cm in depth are found. In this paper, the soils of these microdepressions are not considered.

The morphological descriptions of the studied soil pits are given below.

Pit 1-1 characterizes the profile of a shallow light solonchakous solonetz (Calcic Solonetz (Albic, Loamic, Cutanic, Differentic, Protosalic). The groundwater depth is 4.02 m. The upper boundary of effervescence is at the depth of 26 cm, and intensive effervescence begins from the depth of 35 cm.

SEL, 0–8(10) cm. Dry; light-gray with yellowish tint; crumble-platy in the upper part and loose powdery in the lower part; light loam; abundant fine roots (the amount of larger roots (>1 mm) is 2–3 per dm^2); the transition is seen from changes in the color and density; distinct wavy boundary.

BSN, 8(10)–23 cm. Slightly dry; dark brown (chocolate-colored); the color becomes lighter upon the soil drying; coarse prismatic (the height of pris-



Soil positions in the catena: (*1*) land surface topography, (*2*) topography of the lake bottom, (*3*) boreholes and soil pits; groundwater level: (*4*) spring 2012 and (*5*) autumn 2012; (*6*)—the zone occupied by tamarisk.

matic peds is up to 3–5 cm) parting to smaller prisms in the horizontal and vertical directions; with glossy coatings on ped faces; fine-porous; dense; silt loam; the peds are covered by glossy coatings and are densely penetrated by fine (<1 mm) roots; the transition is seen from changes in the color, density, and structure; wavy boundary.

BSNdc, 23–32 cm. Slightly moist; brown (lighter than the overlying horizon); prismatic; the structure becomes less distinct in the lower part; compact silty loam with sandy particles; fine roots; in the lower part, the brown material slightly effervesces; the transition is seen from the appearance of whitish salt efflorescence.

BCAs, 32–55 cm. Slightly moist; yellowish-brown (the color becomes lighter upon soil drying); mottled in the upper part (because of abundant salt efflorescence and whitish yellow carbonate concentrations of 5 mm in diameters); less compact; loose coarse blocky structure; single roots; diffuse boundary.

BCs, 55–80 cm. Slightly moist; brownish yellow sandy silt loam with mainly vertical snowy-white salt veins clustered in concentrations of 3–5 cm in diameter; the transition is seen from changes in the color and texture; clear smooth boundary.

Cs, 80–100 cm. Slightly dry; pale yellow; crumb structure; slightly compact; with whitish gypsum veins in the lower part; no roots.

This soil profile is underlain by stratified lacustrine–alluvial sediments of different textures.

Pit 1-2 characterizes the profile of a shallow light solonchakous solonetz (Calcic Solonetz (Albic, Loamic, Cutanic, Differentic, Protosalic). The upper boundary of effervescence is at the depth of 26–28 cm. The groundwater table is found at the depth of 1.81 m.

SEL, 0–10 cm. Dry; light gray; fine crumble structure in the upper part and platy structure in the lower part; slightly compact silt loam; many fine roots; the transition is seen from changes in the color and density; uneven boundary.

BSN, 10–26(29) cm. Slightly dry; dark-brown (reddish-brown in the deep part); columnar (columns with white heads disintegrate into prisms in the horizontal direction), compact silt loam; dark-brown glossy films on the sides of peds; fine roots; effervescent in the lower part; the transition is seen from changes in the color; uneven boundary.

BCAs, 29–50 cm. Slightly moist; brown; coarse blocky-prismatic; compact heavy loam; white salt veins (<1 mm in diameter) of predominantly vertical orientation; few roots; diffuse boundary.

BCs, 50–75 cm. Slightly moist; brown; loose coarse blocky; compact heavy loam; single shell fragments at the depth of 60 cm; snowy-white veins of fine-crystalline gypsum (3–4 veins per dm^2) appear from the depth of 70 cm.

Pit 1-3 characterizes a medium-deep light-humus deeply solonchakous solonetz (Calcic Solonetz (Loamic, Cutanic, Differentic, Bathyprotosalic)). The groundwater depth is 1.57 m. The upper boundary of effervescence is at the depth of 43 cm. There are vole burrows near the soil pit, and their nest chamber is cut by the side wall of the pit.

AJ, 0–20 cm. A fragmentary sod layer is formed under bunch grasses; Dry; light gray; coarse angular blocky with powdery structural elements; compact light loam; abundant fine roots; aggregate pores are not numerous; the transition is seen from changes in the soil bulk density; smooth boundary.

SEL, 20–27 cm. Dry; light-gray (darker than the AJ horizon); very compact; coarse angular blocky structure; light loam; few roots; smooth boundary.

BSN, 27–43 cm. Slightly dry grayish dark brown silt loam; prismatic structure parting to smaller angular blocks (nuts); the peds are very compact and are covered by clay–humus films; fine roots are concentrated on the surface of the peds; on the left side wall, there is a vole nest chamber filled with plant remains at the depth of 32–40 cm; the transition is seen from changes in the color and from the appearance of effervescence; smooth boundary.

BCAs, 43–80 cm. Slightly moist;, brown (light-brown in the lower part); compact, coarse crumb structure; loose medium loam (heavy loam in the lower part); whitish veins of salt concentrations and slightly pronounced irregular yellowish white carbonate concentrations of 5–8 mm in diameter appear from the depth of 50 cm; in the deep part, veins (1 mm in diameter) and rounded concentrations (3–5 mm in diameter) of small-crystalline gypsum appear (15–20 concentrations per dm^2); few roots.

Pit 1-4 characterizes the profile of a shallow light-humus quasi-gleyed solonchakous solonetz (Calcic Solonetz (Albic, Loamic, Cutanic, Differentic, Protosalic)). The groundwater depth is 1.34 m. The upper boundary of effervescence is at the depth of 20 cm, and active effervescence is seen from the depth of 26 cm. This pit is found in the area with high digging activity of voles (the surface of the first terrace is almost completely covered by their holes).

AJ, 0–7 cm. Dry; gray; crumb–scale structure with powdery elements; loose light loam; abundant roots; distinct smooth boundary.

SEL, 7–12(13) cm. Dry; whitish gray; crumb–platy structure; compact, porous medium loam; many roots; smooth boundary.

BSNq, 12(13)–23 cm. Slightly dry; dark brown with dove tint; columnar (10-cm-high columns are parting to smaller prisms); compact medium loam; ped faces are covered by dark-brown clay–humus coatings; abundant roots; the transition is seen from changes in the density and color; smooth boundary.

BMs,q, 23–40 cm. Slightly dry; unevenly colored: vertically oriented whitish concentrations of salts along the roots are clearly seen against the background bluish gray color; loose; angular blocky–crumb structure; compact silty to clayey loam; contains brown mottles (3 cm in diameter) of zoogenic origin, the amount of which increases in the lower part of the horizon; clear uneven boundary.

BCs, q, 40–50 cm. Slightly dry; unevenly colored (bluish gray mole tunnels of 9 cm in diameter against brown background soil mass); less compact, coarse angular blocky with a tendency for platy structure; medium to heavy loam; abundant rounded salt concentrations, though their amount is smaller than in the overlying horizon; occasional shells; the transition is seen from changes in the background color; uneven boundary.

Cs, 50–68 cm. Slightly moist; yellowish-brown; light loam with loose blocky structure parting to crumbs; strongly effervescent; single roots; salt veins and concentrations of irregular shape; small (4 mm) carbonate nodules.

Pit 1-5 characterizes the profile of a humus-stratified gleyed solonchak (Calcic Gypsic Gleyic Solonchak (Loamic, Chloridic, Novic). The groundwater is at the depth of 19 cm. Effervescence is seen from the surface.

RJs, 0–6(9) cm. Wet; brown; fine crumb structure; soft plastic heavy loam with a tendency for horizontal layering; few roots (up to 1 mm in diameter); round pores (5–8 pores per cm^2); shell detritus; distinct wavy boundary.

Gox,s, 9–19 cm. Wet; light yellow; coarse angular blocky; relatively soft and plastic heavy loam; inclusions of shell fragments; bluish white soft irregular fine-crystalline salt concentrations (5 mm in diameter) and brownish black iron–manganic nodules (2–5 mm in diameter; 10–15 nodules per dm^2); tamarisk roots up to 10 mm in diameter (5–10 roots per dm^2), and rusty iron concentrations around root channels; smooth boundary.

Gs, 19–37 cm. Satiated wet; whitish blue with rusty brown interlayers; coarse crumb structure; soft plastic medium (light) loam; many tamarisk roots of up to 1 mm in diameter (20–30 roots per dm^2); Rounded pores (4–6 per cm^2) are 0.5–1 mm in diameter; rusty mottles on ped faces; salt concentrations; water seeps from root channels; shell fragments are absent.

The profiles of solonetzes in the upper part of the catena (pits 1-1 and 1-2) are clearly differentiated into horizons typical of these soils, including a well-pronounced solonetzic horizon with columnar structure; The soil in pit 1-3 differs by a higher compaction and a prismatic structure of the solonetzic horizon parting into smaller angular blocky units, a lower boundary of carbonates and salt concentrations, and a clearly developed light-humus AJ horizon (0–20 cm). These morphological features are related to the combined effect of digging animals and vegetation. Grasses actively grow on the ground removed from burrows. The amount of atmospheric moisture accumulated under this denser grass cover is greater than that under low and thin vegetation of the solonetzes on the elevated positions. Moistening conditions in the transi-

Table 1. Composition of water extract (1 : 5) in soils of the catena on the eastern coast of Lake Bulukhta

Horizon	Depth, cm	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	Total salts	Total toxic salts	Salt chemistry	Salinization degree
		cmol(equiv.)/kg							%			
Shallow light-colored solonchakous solonetz (pit 1-1)												
SEL	2–10	0	0.3	0.62	4.3	1	0.8	3.4	0.36	0.15	Nonsaline	Nonsaline
BSN	12–20	0	0.1	2.18	4.9	0.8	0.5	5.9	0.48	0.24	Sulfate–sodium	Slight
BSNdc	20–30	0.2	0.3	6.24	6.1	1.3	2.1	9.5	0.81	0.52	Sulfate–chloride–sodium	Medium
BCAs	35–50	0.9	0	10.19	10.4	9.6	11.8	0.1	1.21	0.74	Chloride–magnesium with gypsum participation	Very strong
BCs	60–80	0	0.5	10.71	9.0	5.5	10.9	3.8	1.17	0.74	Chloride–magnesium with gypsum participation	"
Cs	80–100	0.2	0.2	5.62	5.9	3.9	4.9	3.0	0.71	0.42	Chloride–sodium–magnesium	Strong
Shallow light-colored slightly solonchakous solonetz (pit 1-2)												
SEL	0–10	0	0	0.62	0.4	0.6	0.3	0.12	0.06	0.03	Nonsaline	Nonsaline
BSN	10–25	0	0	1.87	0.3	1.6	0.5	0.07	0.12	0.07	Chloride–calcium	Slight
BCAs	30–50	0.15	0.5	14.04	10.4	14.0	7.8	3.3	1.48	0.67	Chloride–sodium–magnesium with gypsum	Ñèëüíàÿ
BCs	50–75	0.05	0.5	16.85	5.5	8.3	6.5	8.0	1.32	0.86	"	Very strong
Medium-deep light-humus medium thick, deeply solonchakous solonetz (pit 1-3)												
AJ	0–20	0	0.6	0.73	0.3	0.8	0.5	0.3	0.103	0.04	Nonsaline	Nonsaline
SEL	20–27	0	0.2	0.94	0.8	1.6	1.3	0	0.13	0.05	"	"
BSN	27–43	0.2	0.1	0.73	0.8	1.5	0.3	0.03	0.108	0.03	"	"
BCAs	43–80	0	0.5	2.7	9.5	7.4	5.2	0.1	0.782	0.16	Chloride–magnesium with gypsum	Medium
Thin light-humus solonchakous quasi-gleyed solonetz (pit 1-4)												
AJ	0–7	0	0.1	0.21	0.5	0.4	0.4	0.01	0.04	0.02	Nonsaline	Nonsaline
SEL/BSN	7–23	0	0	2.6	1.0	1.3	1.0	1.3	0.21	0.14	Chloride–magnesium–sodium	Medium
BMs,q	23–28	0.1	0.2	10.3	1.7	2.9	0.3	9.2	0.73	0.58	Chloride–sodium	Strong
BÌs,q/BCs,q	28–50	0	0.9	22.57	8.1	16.1	8.3	7.17	1.83	1.06	Chloride–sodium–magnesium with gypsum	Very strong
Cs	50–68	0	0.5	30.58	11.7	16.6	11.4	14.78	2.49	1.56	Chloride–magnesium–sodium with gypsum	"
Humus-stratified gleyed solonchak (pit 1-5)												
RJs	0–9	0.1	1.0	40.77	8.6	13.3	14.8	22.37	2.88	2.14	Chloride–sodium with gypsum	Very strong
Gox,s	9–19	0.1	0.3	12.38	8.7	13.0	3.6	4.88	1.29	0.59	"	Strong
Gs	19–37	0	0.6	22.98	10.8	16.4	11.4	6.58	1.99	1.10	Chloride–magnesium with gypsum	Very strong

Table 2. The contents of carbonates, gypsum, organic matter, and exchangeable bases and pH in soils of the eastern coast of Lake Bulukhta

Horizon	Depth, cm	pH water	C_{org}	$CaCO_3$	Gypsum	Ca^{2+}	Mg^{2+}	Na^+	K^+	S	Exchange-able Na, %
			%			cmol(+)/kg					
Shallow light-colored solonchakous solonetz (pit 1-1)											
SEL	2–10	7.37	0.80	Not det.		5.63	2.67	1	0.49	9.79	10
BSN	12–20	8.57	1.05	″		6.82	8.77	10.62	0.31	26.52	40
BSNdc	20–30	8.68	0.91	″		6.83	2.48	10.09	0.73	20.13	50
BCAs	35–50	8.91	0.30	13.17	5.00	Not det.					
BCs	60–80	8.91	Not det.	17.66	1.43	″					
Cs	80–100	8.98	″	7.40	Not det.	″					
Shallow light-colored slightly solonchakous solonetz (pit 1-2)											
SEL	0–10	8.29	1.05	Not det.		4.65	8.37	9.24	0.36	22.62	41
BSN	10–25	9.21	1.04	″		6.22	6.43	11.26	0.56	24.47	46
BCAs	30–50	8.75	0.32	″	7.1	Not det.					
BCs	50–75	8.63	Not det.	″	1.38	″					
Medium-deep light-humus solonetz (pit 1-3)											
AJ	0–20	7.61	1.62	Not det.		7.4	3.24	0.55	1.31	12.5	4
SEL	20–27	8.4	0.99	″		7.17	3.13	1.77	0.73	12.8	14
BSN	27–43	8.83	1.01	″		10.39	6.43	5.21	0.75	22.78	23
BCAs	43–80	8.29	0.31	″	3.84	Not det.					
Thin light-humus solonchakous quasi-gleyed solonetz (pit 1-4)											
AJ	0–7	7.77	5.69	Not det.		9.42	4.87	2.1	2.27	18.66	11
SEL/BSN	7–23	9.03	1.93	″		6.73	5.15	7.79	1.36	21.03	37
BMs,q	23–28	8.68	Not det.	4.59	″	5.1	1.83	1.93	0.62	9.48	20
BÌs,q/BCs,q	28–50	8.54	″	10.78	4.41	Not det.					
Cs	50–68	8.58	″	18.39	11.6	″					
Humus-stratified gleyed solonchak (pit 1-5)											
RJs	0–9	8.03	1.19	13.78	1.25	Not det.					
Gs,ox	9–19	8.24	0.29	14.78	7.60	″					
Gs	19–37	8.27	0.17	11.58	Not det.	″					

tional positions on slopes are better than in the eluvial positions, which results in salt leaching, considerable compaction of soil horizons, and the destruction of the columnar structure of the solonetzic horizon. Similar transformations of soils in zoogenically turbated areas are described in [1, 4, 5, 14, 17, 26, 27]. The development of the humus horizon is related to richer grass vegetation.

The profile of the solonetz on the first terrace (pit 1-4) is characterized by little thickness, well-pronounced gray-humus horizon, numerous evidences of animal activity (mole passages and tunnels and chambers of invertebrates). The shallow groundwater level is responsible for the high boundary of salts and the presence of hydromorphic features in the form of steel tint of the color of the horizons: the humus horizon becomes darker, and the solonetzic horizon becomes bluish brown.

The humus horizons in pits 1-3 and 1-4 are formed under better conditions in the subordinate (accumulative) positions. A better moisture supply of the soils is also related to the numerous holes of small rodents. Water intensively penetrates into the soil profile through these holes [7]. In addition, rodents add organic matter in the form of their foodstuffs, litter, and excrement and, hence, favor the formation of humic substances in the soils [2, 26, 27].

The solonchak on the lake bottom (pit 1-5) is characterized by intensive gleying and numerous concentrations of soluble salts, gypsum, and iron–manganic nodules. A thin grayish brown humus horizon is formed under the impact of the cliff erosion and transportation of eroded humus-containing material from the first terrace. Tamarisk communities are developed on these deposits formed on the shores of the lake.

Chemical properties. Data on the chemical composition and contents of salts in the studied soils are given in Table 1. In the solonetzes of the eluvial position (pit 1-1), the SEL solonetzic-eluvial horizon is not saline, and the BSN horizon (10–20 cm) is slightly saline (sulfate–sodium salinization). The BSNdc solonetzic horizon (20–30 cm) is characterized by sulfate–chloride–sodium salinization with the content of toxic salts of up to 0.52%. The highest amount of toxic salts (up to 0.74%) is in the subsolonetzic horizons, where salinization is strong with a predominance of chlorine and magnesium ions and with the presence of gypsum. In the sandy parent material, the content of toxic salts drops to 0.43%, and magnesium and sodium predominate among the cations. The highest amount of carbonates and gypsum is accumulated in the subsolonetzic horizons: the content of carbonates in the BCAs and BCs horizons is 13.2 and 17.6% of the soil mass, respectively, and the gypsum content is 5 and 1.43%, respectively (Table 2). In the soil-forming rock, the contents of carbonates and gypsum are lower.

In the light shallow slightly solonchakous solonetz (pit 1-2) of the transitional position, the upper solonetzic-eluvial horizon is also nonsaline. The solonetzic horizon is slightly saline (chloride–calcium salinization), and the salt content in it is 3–4 times lower than that in the solonetzic horizon of the solonetz on the second terrace. The subsolonetzic horizons are characterized by strong chloride–magnesium salinization with gypsum. While the total salt content in them is higher, the content of toxic salts in the BCAs horizon (30–50 cm) is lower than that in the analogous horizon of pit 1-1. The total content of salts in these horizons is higher due to nontoxic calcium sulfates dissolved in the water extract. The gypsum content in the BCAs and BCs horizons is 7.1 and 1.38%, respectively. A lower content of soluble salts in the upper horizons of pit 1-2 is related to better moistening conditions in the transitional landscape position.

Among the studied soils, the light-humus medium-deep solonetz (pit 1-3) of the transitional position developed under grass community is characterized by the most active salt leaching. Soluble salts are absent in the upper 43 cm of the soil profile. They appear in the BCAs (subsolonetzic) horizon. The salinization is of the chloride–magnesium type with gypsum. The content of toxic salts in this horizon is 0.16%, which corresponds to the medium degree of salinization. The gypsum content in the BCAs horizon is 3.84%. Salts are leached off from this soil because of its subordinate topographic position and additional moisture inflow through rodent holes.

In the soil of the first terrace (pit 1-4), the AJ humus horizon (0–7 cm) is not saline. The solonetzic horizon is moderately saline by salts of the chloride–sodium composition. In the lower BCs horizon (28–50 cm), the amount of toxic salts rises sharply up to 1%, which corresponds to very strong salinization. The content of carbonates in this horizon is 10.78%, and the gypsum content is 4.41 %. The Cs horizon is characterized by the greatest accumulation of soluble salts (the content of toxic salts is 1.56%), carbonates (18.39%), and gypsum (11.6%).

The soils of the superaqual landscapes are most saline among the soils of the catena. These are gley humus-stratified solonchaks characterized by the strong chloride–sodium salinization from the surface. The sum of toxic salts in the upper RJs horizon is as high as 2.1% and decreases to 0.6% in the lower Gox,s horizon. Deeper, in the Gs horizon, magnesium chlorides predominate in the chemical composition of salts and the content of toxic salts rises to 1.1%. The gypsum content is high in the entire soil profile (11–13%). The content of carbonates is low in the RJs horizon (1.2%) and increases up to 7.6% in the Gox,s horizon. The high degree of salinization rate is caused by the presence of shallow strongly saline groundwater. The studied solonetzes are assigned to the group of high-gypsum soils (according to the upper boundary of gypsiferous horizons) and moderately calcareous (with respect to the carbonate content) soils.

Thus, the solonetz of the autonomous (eluvial) position is characterized by the sulfate–sodium salinization in upper part and chloride–magnesium salinization in the subsolonetzic horizons. Sulfate–sodium salinization is the evidence of the continental type of salt accumulation typical of meadow-steppe eluvial landscapes with deep sulfate–sodium groundwater [24] (the area of the Dzhanybek Experimental Station of the Institute of Forestry, Russian Academy of Sciences). The formation of sulfate–sodium salinization is obviously related to the lithological heterogeneity of the parent materials, which retards the migration of the film–capillary water from the groundwater. In the upper horizons of this solonetz, the chemical composition of salts is transformed because of the interaction between the atmospheric precipitation and the initial residual soil and groundwater solutions. However, this process is restricted by the compact solonetzic horizon and the small depth of atmospheric moisture penetration. Such a specific alternation of the chemical composition of salts in sediments of the nonuniform lithological composition has already been described for the soils of the second terrace of Khaki Playa [26]. In the soils of the subordinate positions with a relatively shallow groundwater table, the accumulation of salts is of the seacoast type with a predominance of chlorides.

The contents and distribution patterns of organic matter in the soils of the studied catena are different. In the solonetz of the eluvial position, the organic matter content reaches its maximum (1%) in the solonetzic horizon, which is typical of the meadow-steppe solonetzic complexes subjected to incomplete desalinization and to solodization [3]. In the subsolonetzic horizons, the organic matter content drops to 0.3%. In the solonetzes of the transitional positions (pits 1-2 and 1-3), the highest contents of organic matter are in the topsoil horizons (1 and 1.6%, respectively). A higher organic matter content in these soils in comparison with the solonetz of the autonomous position is explained by the better water supply of plants with the development of richer grassy vegetation and, hence, higher input of plant debris into the soils. In addition, the greater organic matter content in pit 1-3 is related to a denser grass community. In the solonetz of the accumulative position, the content of organic matter is as high as 5% in the upper 7-cm-thick layer. The solonchak on the lake bottom is characterized by relatively high humus content in the RJs horizon

Table 3. Elementary soil processes in soils of the catena

Elementary soil process	Eluvial (pit 1-1)	Transitional (pit 1-2)	Transitional (pit 1-3)	Accumulative (pit 1-4)	Superaqual (pit 1-5)
Organic matter accumulation	+	++	+++	++++	++
Salinization	++	++	+	+++	++++
Desalinization	+	++	+++	+	Absent
Solonetzization	+++	+++	+	++	Absent
Desolonetzization	Absent	Absent	++	+	Absent
Gleying	Absent	Absent	Absent	+	+++
Accumulation of carbonates	++	++	+	+++	++++
Gypsum accumulation	++	++	+	+++	++++

The number of (+) signs signifies the intensity of elementary soil processes.

Table 4. Groundwater level (GWL) and salinity in soils of the catena in 2012–2013

Sampling date	GWL, m	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	Salinity, g/L
		mmol(equiv.)/L							
Shallow light-colored, solonchakous solonetz (pit 1-1)									
07.05.2012	4.02	0.9	20	267.8	11.25	–	–	153	–
03.10.2012	4.5	1	5.6	235.8	66	36.5	92.5	179.4	17.88
29.04.2013	4.2	–	–	–	–	–	–	–	–
27.06.2013	4.5	0.8	4.8	231.6	9	31	97	118	13.47
23.09.2013	4.76	1	4.8	233.2	71	47	71	193	18.22
Shallow light-colored slightly solonchakous solonetz (pit 1-2)									
07.05.2012	1.81	0	9	273.5	51.88	49.38	95.6	189.4	19.24
03.10.2012	2.38	3	6.6	294.8	26	24	117.5	188.9	18.44
29.04.2013	2.02	0	2.4	135.2	12	44	55	50.6	8.23
27.06.2013	2.44	0.8	2.8	203.6	27	47	67	120.2	13.23
23.09.2013	2.47	1	6.8	215.2	34	81	60	117	14.73
Medium-deep light-humusdeeply solonchakous solonetz (pit 1-3)									
07.05.2012	1.57	0.6	11	157	91.9	28.75	58.7	173	15.93
03.10.2012	2.11	1	4.6	232.8	73.5	16.5	82.5	212.9	18.32
29.04.2013	1.71	0.8	10.8	96.8	18	27	46	53.4	7.3
27.06.2013	2.03	1.6	12	189.6	12	23	90	102.2	11.98
23.09.2013	2.18	1.2	8	397.2	84	70	97	324.4	28.66
Thin light-humus solonchakous, quasi-gleyed solonetz (pit 1-4)									
07.05.2012	1.34	0	12.75	541.7	51.88	73.75	175.63	357	34.29
03.10.2012	1.58	1	6.6	386.8	66	34	137.5	288.9	26.31
29.04.2013	1.32	1.6	6	679.4	9	79	199	418.2	38.56
27.06.2013	1.75	0.4	4.4	386	15	51	115	239.8	22.62
23.09.2013	1.64	0.8	6.4	474.8	79	66	125	371	32.39
Humus-stratified gleyed solonchak (pit 1-5)									
07.05.2012	0.19	0	17	714.2	92.5	56.25	210	557.5	47.3
03.10.2012	0.72	1	15.6	369.8	61	44	115	288.4	25.93
29.04.2013	0.42	0.8	7.2	878.4	7	52	252	589.4	49.6
27.06.2013	0.78	0.8	4.4	376	18	43	118	236.2	22.26
23.09.2013	0.49	1.2	6	408.8	81	45	116	338.6	28.95

Dashes signify the absence of data.

(1.2%) and its sharp drop down to 0.3% in the deeper horizons. The organic matter is transported to this soil from the first terrace as a result of erosional processes.

Therefore, the organic matter content increases from the soils of eluvial positions to the soils of accumulative positions and decreases in the superaqual landscape, where the accumulation of humus is hampered by the high soil salinity and depends on the rate of the organic matter input from the first terrace as a result of erosion, as well as on periodicity of filling of the lake with snowmelt or rain water.

The studied soils are characterized by the alkaline reaction: slightly alkaline (7.4–7.8) in the topsoil horizons and alkaline and strongly alkaline (8.6–9.2) in the solonetzic and subsolonetzic horizons.

The effective capacity of cation exchange in the upper horizons of the solonetzes of the studied catena is 9.48–26.52 cmol(+)/kg, which corresponds to the data on solonetzes of the northern Caspian area at the Dzhanybek Experimental Station [18] and on the Ergeni Upland [20]. The content of exchangeable sodium in these soils corresponds to the category of high-sodium solonetzes. The only exception is the solonetz under grass vegetation (pit 1-3), which is assigned to medium-sodium solonetzes. The highest cation exchange capacity is seen in the solonetzic horizons with the high content of clay material and high exchange capacity of the organic matter. The soil profiles are also differentiated by the content of exchangeable sodium: its content is the highest in the solonetzic horizons. The absolute contents of exchangeable sodium in the studied solonetzes are similar to those in solonetzes of the Dzhanybek Experimental Station [18].

The differences in the morphological and chemical characteristics between the studied soils can be explained by the differences in elementary pedogenetic processes acting in these soils (Table 3). In the subordinate positions, better water supply causes soil desalinization to a greater depth in comparison with solonetzes in the eluvial positions. In the areas of zoogenic activity, soil desalinization and desolonetzization are enhanced, which results in the transformation of soil morphology with a decrease in the content of exchangeable sodium. In the soils of the accumulative position, where the groundwater level is higher, the zoogenic activity is restricted to a shallow depth. On the bottom of the lake, intensive salinization is accompanied by the organic matter accumulation due to erosion.

The dynamics of the groundwater level, composition, and salinity. The chemical composition of the groundwater under all the studied soils is similar and is characterized by a predominance of sodium chlorides (Table 4). The groundwater salinity is high [15] and close to brines in the superaqual landscapes. The groundwater depth decreases, and the groundwater salinity increases in the direction from the second terrace towards the lake. The studied soils are closely related to the groundwater characteristics. The chemical composition of salts in the lake is similar to that in the groundwater. The concentration of sodium and chlorine ions in the soils and groundwater increases towards the lake (Tables 3 and 4).

Seasonal observations attest to considerable seasonal dynamics of the groundwater composition, level, and salinity. In the eluvial and transitional positions, the groundwater level drops by 0.4–0.5 m from the spring to the fall, and the groundwater salinity increases because of the water expenditure for vegetation and physical evaporation.

In the accumulative and superaqual positions, the groundwater dynamics are different: the groundwater salinity increases upon the rise in the groundwater level, whereas the drop in the groundwater level is accompanied by a decrease in the groundwater salinity.

The highest groundwater level and salinity in these landscape positions are observed in spring, during the highest water level in the lake (Table 4). By the fall, a larger part of the bottom of the lake becomes dry, and the groundwater level and salinity considerably decrease. This is probably related to the outflow of saline water from the lake because of its intensive drying in summer. The groundwater salinity mainly decreases at the expense of a drop in the concentrations of chlorine, sodium, and magnesium ions. Investigations of 2013 showed that the lowest groundwater level and salinity in the studied landscapes were at the end of June. In the fall, they somewhat increased but did not exceed the spring levels. August and September in 2013 were rainy, and the lake was once more filled with water. This caused the autumn rise in the groundwater level and salinity in the accumulative and superaqual landscapes. The relation of groundwater with saline lake water is confirmed by the composition of ions. The concentrations of ions that predominate in the chemical composition of lake water are subjected to the most pronounced seasonal changes.

Therefore, in the accumulative and superaqual landscapes, the dynamics of the groundwater level and salinity depend on the hydrological regime of the lake, which is determined by the amount and seasonal distribution of precipitation.

CONCLUSIONS

(1) Soil-forming conditions within geochemically conjugated landscapes in the coastal zone of salt Lake Bulukhta favor the development of soils with different physicochemical and morphological properties. The terraces of the lake are occupied by solonetzes differing at the species level in the depth of the salt-bearing horizon, the presence and thickness of the humus horizon, the degree of solonetzicity, and the features of hydromorphism. On the lake bottom, solonchaks with thin humus horizon are formed under tamarisk communities.

(2) In the considered soil sequence, the organic matter content increases from the eluvial to the accumulative landscapes. The accumulation of organic matter is most intensive in semihydromorphic soils of the accumulative landscapes with the highest zoogenic activity. In hydromorphic soils of the superaqual landscapes, humus accumulation is dampened by the high salinity and depends on the intensity of the organic matter input with eroded sediments from the first terrace.

(3) Salinization—desalinization, solonetzic process, humus accumulation, and gleyzation are the main pedogenetic processes in the studied catena. The intensity of these processes in different parts of the catena depends on the topographic position of the soils, the level and salinity of the groundwater, the hydrological regime of the lake, and the zoogenic activity. The combined effect of zoogenic and phytogenic factors favors dampening of the solonetzic process, which causes a drop in the content of exchangeable sodium and the replacement of the columnar structure of the solonetzic horizon by the prismatic—angular blocky structure.

(4) The studied soils differ in the degrees of their salinity and in the chemical composition of soluble salts. Soils of the eluvial positions are characterized by the sulfate salinization in the upper part of the profile and chloride salinization in the lower part of the profile. Soils of the subordinate landscapes are mainly characterized by the chloride salinization. Active accumulation of salts in their lower part is accompanied by desalinization of the upper horizons under the impact of additional moistening and local soil water supply through zoogenic holes. In hydromorphic soils of the superaqual landscapes, where the groundwater mineralization is the highest, salinization processes predominate.

(5) The seasonal dynamics of the groundwater level and salinity are different in the soils of the catena. In the accumulative and superaqual positions, the groundwater level and salinity are highly dynamic, and these dynamics are related to the hydrological regime of the lake. In the transitional positions, the groundwater regime is controlled both by the regime of the salt lake water and by the water supply from the higher positions. In the eluvial landscape, the groundwater regime is not affected by the salt lake water. The groundwater level gradually decreases and the groundwater salinity increases during the growing season.

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