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GENESIS AND GEOGRAPHY OF SOILS

# Salinization as the Main Soil-Forming Process in Soils of Natural Oases in the Gobi Desert

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**Abstract**—The saline soils of the natural Ekhiin-Gol oasis located in southern deserts of the Mongolian Trans-Altai Gobi are characterized. Specific features and the genesis of hydromorphic solonchaks, dark-colored meadow, and takyr-like desert soils predominating in the territory of the oasis are considered. Within the Ekhiin-Gol oasis, hydromorphic solonchaks occupy more than 50% of its area. They are formed in the zone of discharge of weakly mineralized groundwater confined to tectonic faults. The upper saline horizon of the solonchaks contains nearly 40–60% of easily soluble salts. Their composition is mainly chloride–sulfate, and their elevated alkalinity is often related to the presence of boron in the soils and groundwater. The mineralogical composition of salts in the solonchaks of the oasis was studied; the reasons for the formation of almost nonsaline dark-colored meadow and takyr-like desert soils along with solonchaks are considered. The water–salt budget was calculated, the distribution of salts along the soil profiles was studied, and reasons for their salinization are considered. The soils of the major part of the Ekhiin-Gol oasis are shown to be subjected to progressing salinization whose intensity depends on the groundwater level and mineralization, as well as on the correlation between the annual evaporation and the amount of water coming to the soil surface with precipitation, groundwater, and water of flooding ice (naled).

*Keywords*: natural oasis, solonchaks (Solonchaks), water–salt budget, naleds (icings), salt profile, composition of salts

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## INTRODUCTION

The encyclopedic dictionary in four languages by Shchukin [35] describes two types of oases: natural and artificial. The formation of the natural oases is related to the natural processes responsible for the additional moistening in desert lands; the formation of artificial oases is associated with the anthropogenic activity, primarily with the development of irrigation. In Mongolian deserts, particularly in the Trans-Altai Gobi, only natural oases are widespread. The term “natural oasis” was first used by Lavrenko and Yunatov [24] when they studied the nature of oases of the Trans-Altai Gobi. They were the first who described natural oases in the Mongolian Gobi desert. The total area of these oases is very small—less than 0.1% of the total area of the region. Oasis ecosystems are mainly formed in the zones of groundwater and springs outcrop. In the Trans-Altai Gobi desert, these zones are mainly confined to tectonic faults [33]. Despite the small area of natural oases in the Gobi desert, their role in the conservation of biodiversity is very important, since they are centers of life in the Gobi desert.

At the same time, current soil processes—the accumulation of salts, in particular—often lead to the destruction of oasis ecosystems.

The aims of our investigations were the detection of specific features of salt accumulation in the soils and the determination of reasons for the existence of almost nonsaline soils (dark-colored meadow and takyr-like desert soils) along with “persistent” solonchaks in the soil cover of the Ekhiin-Gol oasis.

Based on the generalization of the previous works, this paper reflects the specificity of salt accumulation as the main and very dynamic soil process.

## OBJECTS AND METHODS

This article is based on the materials obtained in long-term soil–geographical investigations in the territory of the Ekhiin-Gol oasis located in extreme arid deserts of the Trans-Altai Gobi in southern Mongolia, and in other desert regions of Central Asia [10–12, 24, 27–30]. Soil-geographic data were supplemented with experimental studies of salt transfer in soils [1–3, 37]. A soil map and maps for the salinization of some soil layers were compiled on a scale of 1 : 10000 [27]. The soil map was digitized using the ARC View 1.3 package; the areas for different types of soils composing the soil cover of the oases studied were calculated (Table 1) [10]. The composition of salts in the solonchaks was deter-

**Table 1.** The areas of the soils studied and their percentage of the total land area in the oasis of Ekhiin-Gol [10] (the names are given according to the soil classification accepted in the Mongolian Expedition [33]

| Soils | Area | |
|---|---|---|
| | ha | % |
| Meadow-boggy | 1.9 | 0.4 |
| Dark-colored meadow | 12.0 | 2.4 |
| Meadow-desert | 2.8 | 0.5 |
| Meadow-desert associated with soils of temporary streams – "sairs" | 5.4 | 1.1 |
| Solonchaks over dark-colored meadow soils | 3.8 | 0.7 |
| Hydromorphic persistent solonchaks | 210.2 | 41.2 |
| Takyric solonchaks with hydromorphic persistent solonchaks | 59.8 | 11.7 |
| Sair soils | 57.4 | 5.6 |
| Takyr-like | 4.7 | 0.9 |
| Residual meadow takyr-like | 16.1 | 3.2 |
| Irrigated takyr-like and residual meadow takyr-like | 1.8 | 0.4 |
| Solonchakous residual meadow takyr-like | 56.7 | 11.1 |
| Desert sandy with takyr-like | 43.9 | 8.6 |
| Extremely aridic | 61.6 | 12.1 |
| Water body area | 0.8 | 0.2 |
| Total area | 510 | 100 |

mined using micromorphological and mineralogical methods [32, 34, 36]. The nature of alkalinity in the soils and waters in the solonchaks was investigated [8, 9, 32]. The influence of freezing on the formation of the salt composition was assessed [17]. The salinization of different types of soils was investigated, and the water and salt budgets were calculated for three soil types of the Ekhiin-Gol oasis [5]. Presently, a new cycle of works for studying the nature of this oasis has been carried out. The materials of previous years and new data obtained in the early twenty-first century should be the base of these investigations. Studies in recent years will allow one to reveal the evolution of natural ecosystems in the oasis. For the solution to this problem, all the materials on the nature and soil processes responsible for the development of the soils in the Ekhiin-Gol oasis should be summarized.

## RESULTS AND DISCUSSIONS

**General information of soils and soil-forming processes in the Ekhiin-Gol oasis**. The oasis of Ekhiin-Gol is located in the southern Trans-Altai Gobi with the extremely arid and ultracontinental climate [6, 13, 33] (Table 2). It is confined to a zone of tectonic fault, where spring water discharges and feeds the groundwater of the oasis [33]. The area of the oasis is 510 ha. Fifteen soil types, according to the classification used in Mongolia, were distinguished within its territory [12, 33].

Persistent hydromorphic solonchaks were revealed to predominate in the territory of the oasis; they are formed due to discharge of weakly mineralized groundwater. Solonchaks occupy more than 50% of the area of the oasis [10]. Along with the solonchaks, there are practically nonsaline dark-colored meadow and weakly saline automorphic takyr-like desert soils with a deep groundwater table.

The following main soil processes characteristic of the oasis pedogenesis are revealed: (1) humification, (2) desertification (desiccation, sealing, and dehumification), and (3) salt accumulation. Their combination and the degree of expression determine properties and evolution of the oasis soils.

The nonsaline and weakly saline dark-colored soils of the oasis are characterized by the most intense humus accumulation, which is not typical for the soils of the desert zone where organic residues are rapidly mineralized. However, the low temperatures of the meadow soils in Gobi oases related to the permanently low temperatures of the weakly mineralized spring waters and the specific features of the climate in Mongolian deserts [6, 13, 33] determine the microclimatic conditions of meadows, the organic matter transformation, and the formation of meadow soils with a high humus content (8%). These soils resemble meadow soils of Western Siberia [23]. In these soils, an intense salt accumulation is not observed due to the natural washing of the soils with fresh spring water, which dis-

**Table 2.** Climatic characteristics of Mongolian deserts [6, 33]

| Deserts | Air temperature, °C | | | Sum of temperatures above 10°C | Number of frostless days | Average precipitation, mm* | Precipitation in June–August, mm | Radiation budget, ccal/cm$^2$ per year |
|---|---|---|---|---|---|---|---|---|
| | year | January | July | | | | | |
| Steppificated | +3 | –18.7 | +23.1 | 2703 | 90 | $\frac{112}{100–130}$ | 78.3 | 39.0 |
| True | +4 | –18.2 | +24.0 | 2996 | 90 | $\frac{90}{70–100}$ | 76.7 | 42.0 |
| Extremely aridic | +8 | –17.0 | +28.0 | 3648 | 100 | $\frac{43}{20–50}$ | 31.0 | 48.0 |

* Above the line is the mean value, under the line are minimum and maximum values.

**Table 3.** Mineralization and the composition of groundwater and spring water in the oasis of Ekhiin-Gol

| Object | Groundwater table, cm | Total salts, mg/L | Alkalinity | | $Cl^-$ | $SO_4^{2-}$ | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+ + K^+$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | $CO_3^{2-}$ | $HCO^-_{3\,total}$ | | | | | |
| | | | mmol(equiv)/L | | | | | | |
| Pit 8 | 180 | 1470.0 | Absent | 3.2 | 9.0 | 11.2 | 5.5 | 1.9 | 15.4 |
| Pit 1 | 250 | 2080.0 | – | 7.6 | 12.0 | 14.1 | 4.3 | 4.3 | 25.1 |
| Pit 17 | 150 | 2897.0 | – | 9.7 | 109.7 | 309.4 | 33.3 | 19.0 | 376.6 |
| Pit 6 | 190 | 2550.0 | – | 2.8 | 12.0 | 23.6 | 10.9 | 4.5 | 22.9 |
| Pit 51 | 130 | 1600.0 | – | 5.4 | 9.2 | 11.2 | 6.9 | 2.4 | 16.5 |
| Pit 47 | 70 | 2372.0 | 0.4 | 2.0 | 5.0 | 27.7 | 16.6 | 6.1 | 12.3 |
| Pit 46 | 180 | 5396.0 | 0.2 | 2.6 | 11.9 | 63.6 | 22.4 | 7.5 | 48.0 |
| Pit 4 | 230 | 3496.0 | 0.8 | 7.0 | 18.0 | 28.4 | 6.8 | 6.6 | 40.8 |
| Spring water | | | | | | | | | |
| Naran-Bulag (pit 47) | From the surface | 896.0 | Absent | 1.8 | 4.8 | 7.0 | 1.0 | 1.7 | 10.0 |
| Ambulak | " | 875.0 | Absent | 2.2 | 4.9 | 6.9 | 3.8 | 1.2 | 9.0 |
| Ekhii-Gol (potable water) | " | 728.0 | 0.2 | 2.4 | 3.5 | 5.6 | 2.6 | 1.3 | 7.8 |

The analyses were performed in the Analytical Laboratory of the Dokuchaev Soil Science Institute.

charges on the soil surface. In winter, spring water freezes, and flood ice (naled) is formed on the soil surface. These naleds thaw only in summer and remove salts from the soils.

The desertification (sealing, desiccation, and humification) determines the formation of takyr-like soils in the oasis. The process of salt accumulation in the takyr-like soils is practically not manifested because of the deep groundwater level and weak eolian transfer of salts.

**The salt accumulation and water–salt budgets in the soils of the oasis**. The salt accumulation in the soils of the oasis is the most intense in the hydromorphic solonchaks that prevail there (Fig. 1). The content of soluble sodium in the solonchaks exceeds 12 and reaches 75 cmol(equiv)/kg and more, which allows one to attribute the oasis solonchaks to the category of persistent ones. The salt accumulation in the solonchaks is related to the predominance of evaporation of weakly mineralized groundwater over the ingress of water to the soil surface. This groundwater is the main source of salts in these soils in spite of their weak mineralization (Table 3). In most soils of the oasis, the salt accumulation is rather intense. However, the presence of the nonsaline meadow soils in the oasis allow one to affirm that the salt accumulation is not a necessary process of the oasis pedogenesis even at the groundwater table close to the surface. In order to understand this phenomenon, the processes of current salt accumulation and factors responsible for them should be considered in more details. Within the oasis, three categories of soils sharply differing in the salt characteristics are distinguished (Fig. 2): solonchaks (pit 46), weakly saline dark-colored meadow (pit 8), and nonsaline or weakly solonchakous takyr-like (pit 44). The differences in the properties of these soils are related to the features of their formation and specificity of the water and salt budgets.

The solonchaks develop under permanent groundwater moistening. i.e. under the predominance of evaporation over the water ingress to the soil surface ($\bar{V} = \dfrac{E}{W} > 1$, where $\bar{V}$ is the ratio of the total evaporation to the amount of water entering the soil; $E$ is the total evaporation, mm; $W$ is $P + B$; $P$ is the total precipitation, mm; $B$ is the water ingress.

The dark-colored meadow soils are formed directly in the zone of discharging spring water with constant temperature (+ 10°C) and low mineralization. In winter, when the air temperature drops to –30°C, naleds are formed from the spring water on the soil surface, and they thaw only in summer. Thawing water is an additional source of moistening, providing a natural leaching of the dark-colored meadow soils. Thus, the ratio $\bar{V} < 1$ means that the soil water regime is percolative.

At the present time, only atmospheric moistening is characteristic of the automorphic takyr-like soils, unlike the hydromorphic ones. In the Trans-Altai Gobi, the annual precipitation is 30 mm ($\bar{V} = 1$). To reveal the causes of the differences in salinity, we consider in detail the general regularities of the formation of the water–salt budgets in these soils. The following conditions were accepted when developing an equation of the water budget ($W = P + B + g$): $W$—the long-term changes in the surface water reserves equal zero, i.e. the current conditions responsible for the water budget do not change for the period studied; $P$—the annual precipitation, 30 mm per year for the Ekhiin-Gol oasis; $B$—the additional water of the spring water (naleds) in winter, 300 mm per year; $E$—the total evaporation calculated by the Aver'yanov's formula [1]

$$E = E_0\left(1 - \frac{h}{H_{cr}}\right)^2,$$

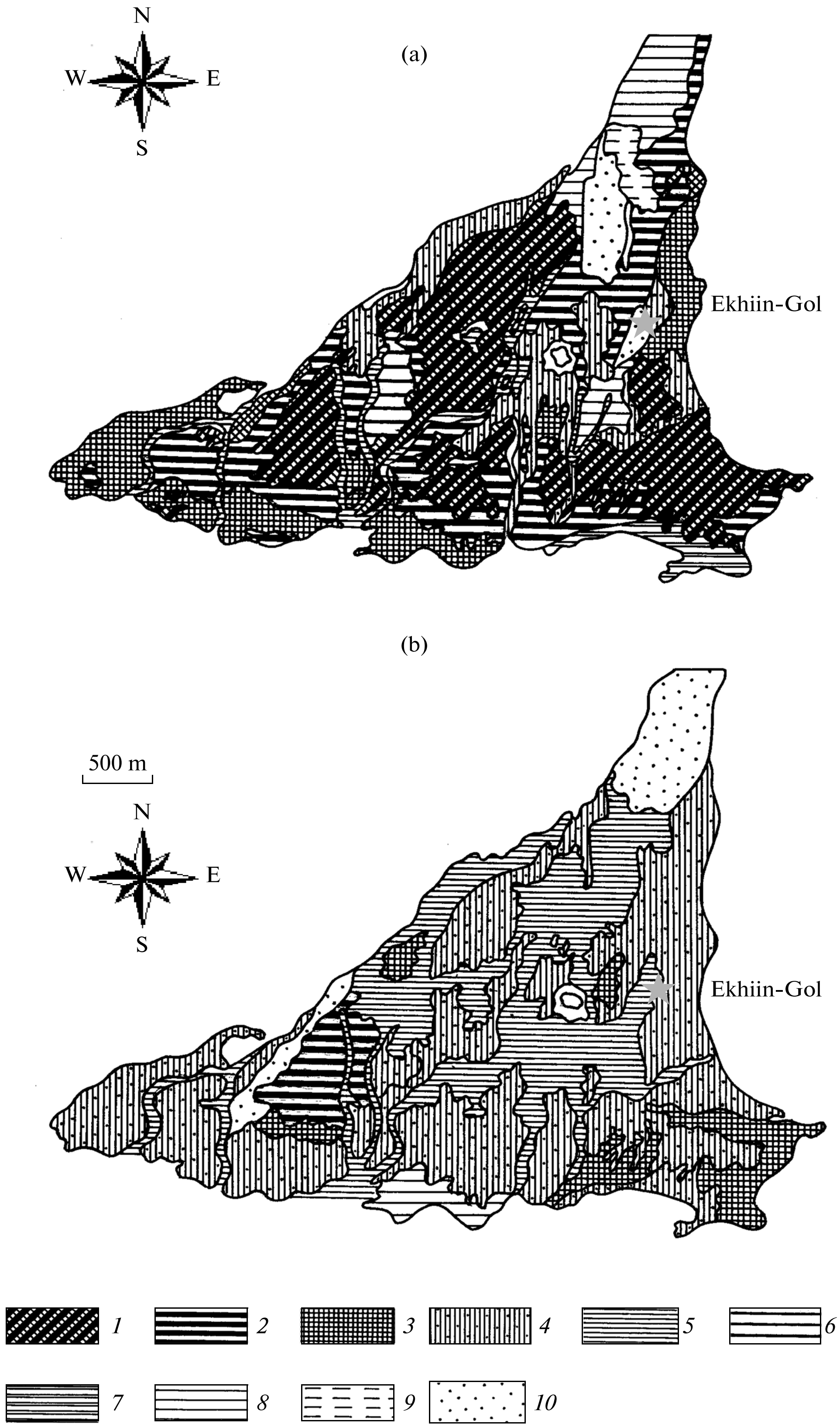


**Fig. 1.** Map of the salinization of the Ekhiin-Gol oasis soils at the depths of (a) 0–100 and (b) 100–200 cm based on the results of the soil–salt survey in 1977. The content of Na in the water extracts (cmol(equiv)/kg): *1*—>75; *2*—35–75; *3*—12–35; *4*—6–12; *5*—2–6; *6*—<2; *7*—35–75 prevail, >75 is in some areas; *8*—6–12, 12–35; *9*—12–35, 2–6; *10*—2–6, 6–12.

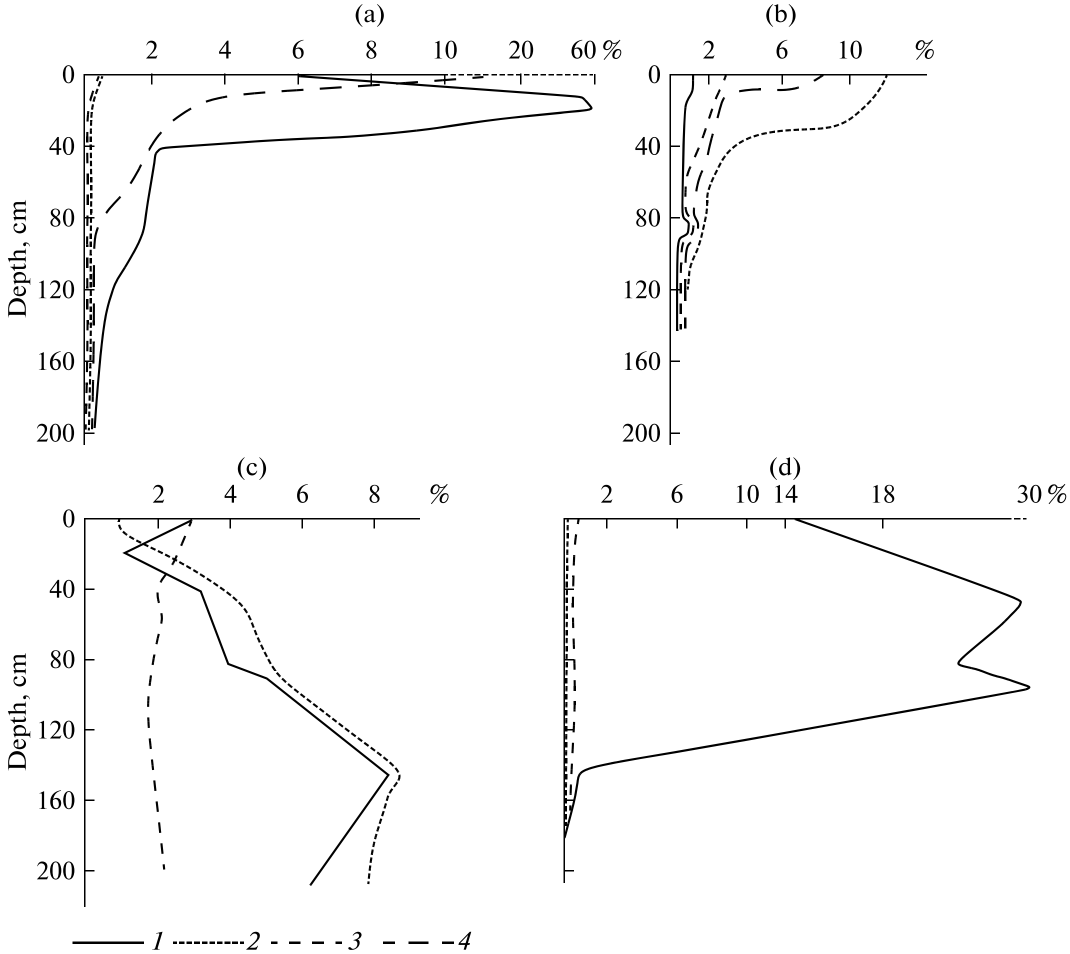


**Fig. 2.** The distribution of (a) easily soluble salts, (b) humus, (c) $CO_2$ of carbonates, and (d) and gypsum in the soils of the Eikhiin-Gol oasis: *1*—persistent solonchak, pit 46 (mineralization of the groundwater is 5.4 g/L); *2*—dark-colored meadow, pit 8 (1.5 g/L); *3*—takyr-like, pit 44 (residual meadow); *4*—meadow solonchak over the dark-colored soil, pit 53 (3.3 g/L).

where $E_0$ is the evaporation capacity calculated according to Ivanov [16] (for extreme arid deserts, it is 1230 mm per year); $h$ is the mean depth of the groundwater table, about 1.8 m under the solonchaks and meadow soils; $H_{cr}$ is the depth of the groundwater, at which an intense evaporation discharge begins (2.5–3.0 m for loess-like loams in the Ekhiin-Gol oasis). For the calculation, the value of 3 m was taken. Thus, the total evaporation calculated by this formula was 197 mm. In each particular case, the value of $g$ (water exchange with groundwater) will change, since $g = E - (P + B)$. In the automorphic conditions (pit 44), $g$ will be zero, as in this case, and the water exchange with groundwater is absent, since the precipitation is fully spent on evaporation. In the solonchaks, precipitation with water entering the soil from the groundwater are spent on evaporation; in the dark-colored meadow soils with winter naleds, precipitation and thawing water are spent for evaporation (Table 4). In the solonchaks, the annual expenditures of the groundwater for evaporation are 167 mm ($\bar{V} > 1$). On the contrary, in the dark-colored soils, the values of $g$ were negative, indicating a percolative water regime with the intensity of about 133 mm per year ($\bar{V} < 1$).

The character of the water exchange ($\bar{V}$) allows speaking about the salt accumulation in the soils and groundwater of the oasis. In the solonchaks, where the groundwater is spent on evaporation continuously, its mineralization is higher than that of spring water. In the meadow soils, groundwater is not spent on evaporation, and its mineralization is close to that of spring water, which was confirmed by experiments. Based on the water budget, a salt budget of the main oasis soils was calculated (Table 5).

The calculations made show that in the solonchaks, the salt budget is positive. Nearly 8.386 t/ha of salts enter the soils from the groundwater annually. In the takyr-like soils, as well as in the zonal automorphic ones, the salt budget is determined by the input of salts with precipitation and eolian dust, since the groundwater table is deep and does not influence salt accumulation. Unfortunately, there are no quantitative

**Table 4.** The characteristics of the water budget in the main types of soils in the oasis of Ekhiin-Gol [5]

| Soil | Groundwater table, cm | $P$ | $B$ | $E$ | $g = E - P - B$ | $\bar{V}$ |
|---|---|---|---|---|---|---|
| | | mm | | | | |
| Solonchak (pit 46) | 1.8 | 30 | – | 197 | +167 | 5.5 |
| Takyr-like (pit 44) | >4.0 | 30 | – | 30 | 0 | 1.0 |
| Dark-colored meadow (pit 8) | 1.8 | 30 | 300 | 197 | –133 | 0.6 |

**Table 5.** The characteristics of the salt budget in the main types of soils in the oasis of Ekhiin-Gol

| Soil | Precipitation, $C_p$ | Groundwater, $C_g$ | Naled's water, $C_V$ | Budget components, t/ha | | | |
|---|---|---|---|---|---|---|---|
| | g/L | | | precipitation, $G_o$ | naled, $G_V$ | groundwater, $G_g$ | $G_n$ |
| Solonchak (pit 46) | 0.12 | 5.0 | Absent | 0.036 | 0 | +8.35 | +8.386 |
| Takyr-like (pit 44) | 0.12 | Absent | " | 0.036 | 0 | 0 | +0.036 |
| Dark-colored meadow (pit 8) | 0.12 | 1.5 | 0.7 | 0.036 | 2.100 | –2.141 | –0.005 |

$G_n = G_p + G_V + G_g$, where $G_n$ is the annual change in the salt reserves; $G_p$ is the ingress of salts with precipitation; $G_V$ is the ingress of salts with surface (naled) water; $G_g$ is salt exchange with groundwater; $C_p$ ins the salt content in precipitation; $C_g$ is the mineralization of groundwater; $C_V$ is the mineralization of naled's water. The mineralization of the water due to thawing naled's water is according to [25]; $G_g$ = 0.16 g/L (from chloride-ion) or 1.6 g/L (from solid residue).

indices characterizing the eolian input of salts. Nevertheless, even minor precipitation (30 mm per year) at the mineralization of 0.12 g/L brings up to 36 kg of salts per year. This fact explains an elevated content of salts in the upper horizons of the automorphic soils in the territory of the oasis and in the arid soils of the adjacent areas.

Quite different conditions are characteristic for the development of the dark-colored meadow soils that are annually percolated with water from thawing naleds. Spring (naled) water is fresh, and its mineralization is lower than that of the groundwater (Table 6). The approximate calculations allow one to reveal the main causes of differences in the current salt accumulation among the oasis soils. Naturally, the changes in any item of the water and salt budgets lead to sharp changes in salt accumulation.

We observed similar phenomena when mapping the soils of the Gobi oases. Drying of oases caused by the decrease of water reserves often occur in the territory of Gobi deserts. In this case, the leaching of the meadow soils with melted water terminates, and their active salinization starts.

In the territory of the oasis, secondary solonchaks were recorded within the areas occupied by the dark-colored meadow soils (pit 53), in places where previously naleds were formed. Nowadays, naleds cease to be formed due to the withdrawal of spring water to a reservoir, and the salt accumulation in the meadow soils became more active. As a result, the meadow soils have been transformed to solonchaks. The lowering of the groundwater level below the critical one stops the salt accumulation, but activates desertification, desiccation, dehumification, and crust-forming. The solonchaks are drying out, beginning the destruction of salt crusts.

Thus, the changes in natural processes induced by the decrease in water resources in the oasis necessarily lead to adverse consequences: in the absence of periodical washing of the soil with water of thawing naleds, the salinity of the soils increases, as well as the area of solonchaks. As the groundwater level is lowered and the soils are not leached, the oasis becomes drier and desertification develops.

The above facts attest that the current salt accumulation may be the most characteristic process in the natural oases of Gobi deserts (including the oasis of Ekhiin-Gol). The combination of close-to-the-surface groundwater and the arid and extremely continental climate typical for Gobi deserts determines the development of salinization characteristic of the hydromorphic soils in arid regions of the world [19, 38–41].

These spring and ground waters feeding the oasis soils, despite their low mineralization (0.3–2.5 g/L), create conditions for the current salt accumulation. A specific feature of the spring waters is their bicarbonate–chloride–sulfate–sodium composition and the frequent presence of boron there. The content of borate ions may reach 5–10 mg/L, exceeding the permissible toxicity limits [40, 41]. Usually, spring waters in the Gobi have a permanent positive temperature (+10°C), even in winter. Therefore, springs continue functioning. Spring water can flow to the soil surface or form groundwater in the surrounding areas. The mineralization of the groundwater compared to the spring water increases but remains rather low (2.5–5.0 g/L); it seldom reaches 15–25 g/L. This phenomenon is observed in the case when the groundwater is found in the areas composed of saline Cretaceous–Paleogene rocks.

The weak mineralization of groundwater in the regions of active salt accumulation is one of the characteristic features of oases in Gobi deserts typical for

**Table 6.** The composition of spring water in the Trans-Altai Gobi

| Object | Total salts, mg/L | Alkalinity | | $Cl^-$ | $SO_4^{2-}$ | $Ca^{2+}$ | $Mg^{++}$ | $Na^+$ | $K^+$ | pH | Boron, mg/L |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $CO_3^{2-}$ | $HCO_3^-$–total | | | | | | | | |
| | | mmol(equiv)/L | | | | | | | | | |
| Tsagan-Bogdo Massif | | | | | | | | | | | |
| Tsagan-Dersei-Khuduk (the depth is 1 m) | 940.72 | 0.23 | 4.30 | 3.48 | 5.61 | 2.70 | 1.80 | 8.70 | 0.20 | 8.05 | 3.05 |
| Mukhar-Dzagai (spring) | 458.01 | Absent | 1.82 | 2.41 | 3.74 | 2.30 | 1.00 | 5.22 | 0.10 | 8.10 | 2.25 |
| Sudzhiin-Bulak (spring) | 380.69 | " | 1.98 | 1.78 | 1.87 | 1.80 | 0.90 | 2.52 | 0.05 | 8.05 | 2.25 |
| Khavisait-Bulak (spring) | 421.31 | " | 2.70 | 1.78 | 1.36 | 2.40 | 0.90 | 2.44 | 0.06 | 8.00 | 1.50 |
| Yaman-Us (spring) | 354.13 | " | 1.79 | 1.78 | 1.70 | 1.70 | 0.80 | 2.35 | 0.06 | 8.10 | 2.25 |
| Alagu-Unen-Khudak | 434.06 | " | 1.82 | 2.17 | 3.91 | 1.60 | 1.20 | | 0.05 | 8.15 | 0.75 |
| Ingeni-Khovrein depression | | | | | | | | | | | |
| Ingeni-Khovrein-Kholoi (a spring in a sair) | 2256.12 | " | 7.18 | 13.67 | 11.90 | 2.00 | 1.00 | 30.45 | 0.26 | 8.00 | 5.25 |
| Ingeni-Khovrein-Bulak | 11428.0 | 0.38 | 6.19 | 86.62 | 86.70 | 19.30 | 17.10 | 139.19 | 0.51 | 8.90 | 10.50 |
| Oases of the Trans-Altai Gobi | | | | | | | | | | | |
| Tsagan-Bugasin-Bulak (a hole in the sair channel) | 1115.12 | 0.30 | 3.08 | 5.33 | 8.16 | 5.00 | 1.80 | 9.57 | 0.12 | 8.20 | 4.50 |
| Shara-Khulsny-Bulak | 1145.84 | Absent | 2.70 | 4.05 | 7.48 | 5.00 | 1.40 | 8.26 | 0.17 | 7.90 | 1.50 |
| Shara-Khulsny-Bulak (a creek bed) | 818.96 | " | 2.39 | 3.55 | 6.12 | 4.30 | 1.10 | 6.52 | 0.13 | 7.90 | 2.25 |

The analyses were performed in the Analytical Laboratory of the Dokuchaev Soil Science Institute (1977). Boron was analyzed by L. Gorenkova in the Department of Soil Chemistry at the Lomonosov Moscow State University (Faculty of Soil Science) using the method of potentiometric titration with mannite [40].

all the deserts of Central Asia [18, 20]. In the oases, the groundwater table is usually at a depth of less than 3 m. As the groundwater is at the depth of 1.5–2.5 m, the capillary fringe reaches the surface, or the depth of 0.5 m from the surface, creating conditions for the intense salt accumulation at the insignificant amount of precipitation. A distinguishing feature of the solonchaks in the oases of Gobi deserts is the low mineralization of groundwater at the high content of salts in soil solutions of the top horizons (Table 7). The main reason of the difference between the mineralization of groundwater and soil solutions is the ratio of the evaporation and the ingress of water to the soil surface ($\bar{V}$) [20]. In Mongolian deserts with an annual precipitation of less than 30 mm (fallen mainly in summer), salts do not reach the groundwater in summer. In winter, the ingress of salts to the soils continues at the expense of freezing out of solutions as it was described in the soils of Siberia [15, 22, 23, 26]. Thus, in the oases of Mongolia, there is a unidirectional movement of salts to the soil surface, which determines the particular features of their salinization, along with the constant low mineralization of the groundwater.

**Salinity of pore solutions in the solonchaks and meadow soils**. The characterization of the salinity of the pore solutions shows that even the persistent solonchaks containing to 40–60% of salts in the surface horizons are formed on rather weakly mineralized groundwater, which has its table at the depth of 1.5–1.8 m. In the lower part of the soil profile, the concentration of pore solutions is low (5–10 g/L) and close to the mineralization and salt composition of the groundwater. However, the concentration of the pore solutions sharply increases at the depth of about 30–50 cm from the surface and reaches 200–300 g/L. It means that the salt concentration gradients in the upper and lower horizons may be enormous, indicating the active salt accumulation only in the upper soil horizons. Supersaturated soil solutions under overheating or overcooling of the upper soil horizons are responsible for the crystallization of salts and their transformation to the solid soil phase. Thus, some conditions for the formation of salt crusts are created in the soils, even at a relatively low content of salts in the lower part of soil profiles. Therefore, the solonchaks' profile in the oases and the formation of salt crusts within their profiles are a result of the current salt accumulation, which is confirmed by experimental results [17, 36] and theoretical studies [2, 4]. In the case when the annual evaporation exceeds the water ingress to the soil surface, the mineralization of pore solutions (especially in the upper soil horizons) will always be higher than the mineralization of the groundwater. Nevertheless, the soil salinization is not unlimited; it depends on the water regime and salt content in the groundwater. On the formation of naleds and a percolative water regime (at the expense of thawing naleds), the mineralization of pore solu-

**Table 7.** The chemical composition of soil solutions of the solonchaks and takyr-like desert soils of the oasis of Ekhiin-Gol

| Depth, cm | Moisture, % | Alkalinity | | $Cl^-$ | $SO_4^{2-}$ | $Ca^{2+}$ | $Mg^{2+}$ | Spectral | | Total salts, g/L |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $CO_3^{2-}$ | $HCO_3^-$–total | | | | | Na | K | |
| | | mmol(equiv)/L | | | | | | | | |
| Takyr-like soil (pit 44) | | | | | | | | | | |
| 0–3 | 17.62 | Absent | 8.4 | 37.8 | 101.9 | 31.2 | 24.0 | 73.9 | Not determined | 9.3 |
| 3–20 | 17.78 | " | 8.6 | 89.9 | 93.6 | 64.9 | 28.8 | 147.9 | " | 13.3 |
| 20–40 | 20.64 | " | 5.0 | 137.7 | 63.4 | 92.5 | 50.5 | 152.2 | " | 14.4 |
| 40–75 | 19.56 | " | 5.9 | 138.7 | 161.0 | 61.2 | 40.8 | 191.4 | " | 19.1 |
| 75–90 | 11.73 | " | 7.9 | 23.9 | 17.5 | 7.2 | 9.6 | 37.0 | " | 3.3 |
| 90–120 | 17.50 | 0.5 | 6.4 | 14.5 | 14.1 | 3.2 | 4.0 | 31.7 | " | 2.4 |
| 120–160 | 16.53 | Absent | 5.0 | 29.9 | 33.1 | 11.4 | 21.1 | 43.5 | " | 4.4 |
| 160–170 | 15.52 | Absent | 3.0 | 78.7 | 58.6 | 33.6 | 27.2 | 75.2 | " | 8.5 |
| Solonchak, pit 4 | | | | | | | | | | |
| 2–7 | 10.94 | Absent | 15.6 | 4740 | 673.5 | 14.0 | 352.7 | 4785.0 | 179.2 | 297.1 |
| 7–12 | 12.51 | Absent | 11.9 | 4530 | 1419.6 | 6.0 | 307.7 | 5763.7 | 121.6 | 346.0 |
| 12–25 | 11.58 | 0.5 | 6.7 | 3320 | 2029.2 | 11.0 | 281.8 | 5220.0 | 89.6 | 324.7 |
| 25–50 | 14.37 | Absent | 6.9 | 1638 | 677.2 | 30.6 | 137.7 | 2172.8 | 42.5 | 136.0 |
| 50–85 | 19.14 | Absent | 3.5 | 580.0 | 331.8 | 33.5 | 64.9 | 793.9 | 12.8 | 53.8 |
| 85–100 | 20.15 | 0.5 | 5.7 | 136.0 | 76.5 | 22.0 | 20.0 | 130.5 | Traces | 12.5 |
| 130–150 | 21.75 | Absent | 3.0 | 32.0 | 36.2 | 12.0 | 7.5 | 43.5 | " | 4.2 |
| 150–200 | 20.82 | Absent | 5.7 | 107.5 | 55.9 | 41.2 | 22.5 | 97.9 | " | 9.6 |
| 200–250 | 21.50 | 0.5 | 7.4 | 53.3 | 33.7 | 15.5 | 10.0 | 57.8 | " | 5.4 |
| Groundwater | | | | | | | | | | |
| 250 | 100 | 0.8 | 7.00 | 18.1 | 2.3 | 6.8 | 6.6 | 40.8 | Absent | 3.5 |
| Solonchak (pit 46) | | | | | | | | | | |
| 3–10 | 23.70 | 23.1 | 83.9 | 3183.5 | 2679.1 | 15.5 | 183.0 | 5621.9 | 340.7 | 385.6 |
| 10–20 | 64.30 | 7.4 | 43.4 | 1650.0 | 1576.4 | 19.8 | 229.8 | 3348.0 | 153.5 | 222.6 |
| 20–40 | 20.60 | 3.5 | 19.9 | 513.6 | 891.8 | 8.9 | 0.9 | 87.0 | 28.6 | 94.9 |
| 40–80 | 26.00 | Absent | 3. 2 | 328.8 | 245.5 | 30.9 | 28.0 | 513.1 | 10.23 | 6.6 |
| 90–150 | 31.80 | 0.5 | 4.0 | 103.2 | 104.3 | 28.9 | 30.0 | 168.8 | 2.6 | 13.8 |
| 150–190 | 22.50 | Absent | 4.0 | 17.0 | 26.0 | 31.1 | 8.7 | 0.9 | 0.0 | 3.7 |
| Groundwater | | | | | | | | | | |
| 190 | 100 | 0.2 | 2.6 | 11.9 | 64.6 | 22.4 | 7. 9 | 48.0 | Absent | 5.4 |

tions turns out to be less than the mineralization of the groundwater (Fig. 3) [4].

The simultaneous characterization of the salt composition in spring water, groundwater, soil solutions, and in the soil solid phase was first made for the assessment of the salinity of solonchaks in Mongolian oases. The chemical nature of the solonchaks was found to be determined by the groundwater composition, which is transformed in the process of evaporation and freezing out [17]. The chemical analyses of soil solutions and water extracts showed that in the soils of the oasis, the chloride–sulfate–sodium and sulfate–sodium salinization prevailed, sometimes with elevated alkalinity; the $HCO_3^-$-ion content is often lower than the sum of calcium and magnesium, testifying to the absence of soda [8, 9]. The presence of some amount of nitrates ($NO_3^-$) was found in the soils and waters of the oasis. Kovda considered this a characteristic feature of the soils in extremely arid deserts [19].

**Salt neoformations in the solonchaks of the oasis**. The investigation of salts in the solid soil phase using micromorphological and mineralogical analyses [32, 34, 36] showed that the solonchaks was characterized by the following features. A brownish hummocky hard crust is formed on the soil surface. It is cemented with fused glassy halite (NaCl) from the surface. The horizons of the maximal accumulation of white fine-crystalline salts under the crust are dominated by sodium sulfate (thenardite $Na_2SO_4$). In the zone of the capillary fringe, a compact horizon cemented with transparent glassy crystals of mirabilite ($Na_2SO_4 \cdot 10H_2O$) is formed. It is preserved in the soil profile during the whole summer, since the soil remains cool. Only in the well-heated upper part of the soil profile are sulfate salts in the form of thenardite. In addition, in the oasis solonchaks, glauberite ($Na_2SO_4 \cdot CaSO_4$) is present. In some pits, sodium borate ($Na_2B_4O_7 \cdot 10H_2O$) was found, confirming the presence of boron in the spring

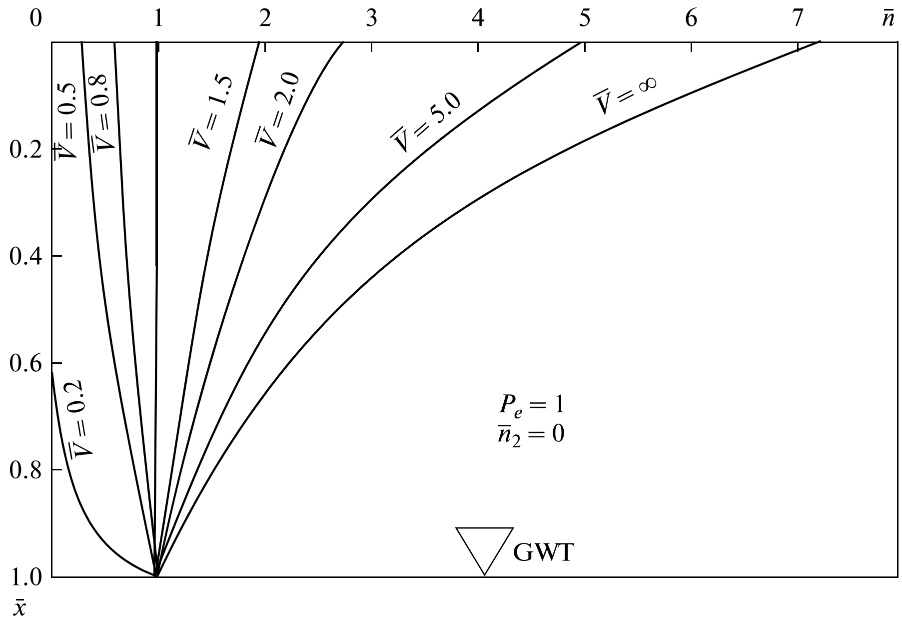


**Fig. 3.** A scheme of the distribution of salts within the soil–ground layer at different $\bar{V}$. $\bar{V}$—the ratio between the evaporation and the sum of total precipitation and irrigation and/or thaw waters of naleds; on axis $y$ is $\bar{x}$ the relative depth from the soil surface. $\bar{x} = \frac{x}{x_1}$; $x$ is the depth from the soil surface, m; $x_1$ is the depth of groundwater, m; on axis $\bar{n}$ is the ratio between the contents of salts in the soil and groundwater [1]; $\bar{n} = n/n_1$, where $n$ is the content of salts in the soil, % or g/L, and $n_1$ is the content of salts in the groundwater, % or g/L; $P_e$ is the dimensionless Peñlet parameter characterizing the salt transfer in the soil; $\bar{n}_2$ is the ratio of the contents of salts in the surface and ground waters; $\bar{n}_2 = n_2/n_1$, where $n_2$ is the content of salts in irrigation water (in the naled's water), % or g/L; $n_1$ is the content of salts in the groundwater, % or g/L.

and ground waters and soils of Gobi oases. This fact was first recorded for the soils of Mongolian oases [36].

The accumulation of gypsum is a special feature of the recent salt accumulation in the oasis soils, which was detected by micromorphological studies. In the chloride and sulfate hydromorphic solonchaks, two forms of gypsum pedofeatures are present, along with those of easily soluble salts: (1) "gypsan" on the pore walls and infillings, and (2) gypsum in the form of small idiomorphic crystals or druses inside the clay micromass. The presence of gypsans testifies to the hydrogenic origin of gypsum. In this case, the mechanism of the gypsum formation is related to the ascending movement of soil solutions. The episodic precipitation (once in several years, 30 mm) excludes the wetting of the soil profiles and the movement of salts and gypsum to the lower horizons. The formation of idiomorphic gypsum crystals and druses within the clay micromass seems to be related to the decalcification. Both forms of gypsum pedofeatures were found in the sulfate and chloride solonchaks of Ekhiin-Gol oasis. However, in the sulfate solonchaks, the hydrogenic gypsum pedofeatures predominated; in the chloride solonchaks, gypsum crystals resulting from the decalcification prevailed [32, 34, 36].

**Alkalinity of the soils in the oasis**. The materials on the salinity of the soils and processes of salt accumulation in the soils of the Gobi oases evidence their certain similarity with the soils of Xinjiang deserts studied earlier by Kovda [18] and Egorov et al. [14]. However, with the absolute similarity of the soils of these regions in salt accumulation, their specificity is firstly related to the salt composition.

Egorov also writes: "The materials on soda salinization collected in the territory of southern Xinjiang for the first time allow distinguishing an original province of soda–chloride–sulfate salinization of the soils and groundwater similar to that described in the world literature" [14, p. 200]. Egorov explains the soda accumulation by the properties of the sediments, namely, the absence of clay particles that are able to sorb sodium. At the same time, Egorov et al. [14], describing the specificity of soil salinization in this province, paid attention to the presence of soda (normal alkalinity) in solutions containing calcium sulfate. In the authors' opinion, this fact needs an additional explanation.

The studies of the soils in the Gobi deserts have revealed an elevated alkalinity, which was often registered in spring and ground waters, soils solutions, and water extracts (Table 8).

The total alkalinity of the solonchaks in the oasis of Ekhiin-Gol determined in water extracts may reach 6 cmol(equiv)/kg; the total alkalinity of soil solutions is 40–80 mmol(equiv)/L. Bespalov [7] attributed pre-

**Table 8.** The composition of the water extract alkalinity from the soils in the Ekhiin-Gol oasis

| Depth, cm | Total salts, g/L | pH water | Alk total | Alk carb | Alk $CO_3$ | Alk bor | Alk org |
|---|---|---|---|---|---|---|---|
| | | | cmol(equiv)/kg | | | | |
| Takyr-like, pit 44 | | | | | | | |
| 20–40 | 0.45 | 7.90 | 0.63 | 0.43/68* | 0.003 | Absent | 0.20/32* |
| 40–75 | 0.21 | 8.85 | 1.69 | 1.40/83 | 0.10 | " | 0.26/15 |
| 90–120 | 0.20 | 8.90 | 1.99 | 1.88/95 | 0.13 | " | 0.06/30 |
| 120–160 | 0.19 | 8.75 | 1.60 | 1.33/83 | 0.09 | " | 0.23/15 |
| Solonchak, pit 4 | | | | | | | |
| 0–2 | 17.80 | 8.50 | 1.88 | 0.49/26 | 0.01 | 0.05/3 | 1.33/71 |
| 2–7 | 13.70 | 8.40 | 1.00 | 0.46/46 | 0.01 | 0.02/2 | 0.51/51 |
| 7–12 | 24.10 | 8.60 | 0.80 | 0.30/38 | 0.01 | 0.05/6 | 0.45/56 |
| 12–25 | 4.80 | 8.50 | 0.73 | 0.22/30 | 0.01 | 0.04/7 | 0.46/63 |
| 25–50 | 2.96 | 8.30 | 0.40 | 0.23/58 | 0.004 | 0.03/8 | 0.13/33 |
| 50–85 | 1.45 | 8.20 | 0.66 | 0.50/76 | 0.01 | 0.01/1 | 0.15/23 |
| Solonchak, pit 46 | | | | | | | |
| 0–3 | 5.51 | 8.80 | 2.00 | 0.73/36 | 0.04 | 0.24/12 | 1.04/52 |
| 3–10 | 50.44 | 9.10 | 5.35 | 0.15/21 | 0.112 | 1.70/32 | 2.50/47 |
| 10–20 | 51.37 | 9.05 | 3.65 | 0.80/22 | 0.08 | 1.30/36 | 1.46/40 |
| 20–40 | 2.06 | 8.40 | 0.43 | 0.14/32 | 0.003 | 0.04/10 | 0.25/58 |
| 80–90 | 1.59 | 7.80 | 0.40 | 0.40/100 | 0.002 | Absent | Absent |
| 90–140 | 0.58 | 7.80 | 0.40 | 0.40/100 | 0.002 | " | " |
| Solonchak, pit 17A | | | | | | | |
| 0–2 | 48.55 | 8.50 | 3.32 | 0.86/26 | 0.02 | 0.20/6 | 2.26/68 |
| 2–15 | 58.26 | 8.20 | 1.69 | 0.90/35 | 0.01 | 0.10/6 | 1.48/60 |
| 15–30 | 18.63 | 8.50 | 1.99 | 0.33/17 | 0.01 | 0.20/10 | 1.36/73 |
| 30–60 | 2.54 | 8.00 | 1.60 | 0.48/23 | 0.004 | 0.30/2 | 1.59/75 |
| 60–80 | 2.02 | 7.70 | 0.63 | 0.24/33 | 0.001 | 0.005/30 | 0.46/64 |
| 80–90 | 1.88 | 7.44 | 1.69 | 0.40/55 | 0.001 | Absent | 0.32/44 |
| 90–120 | 1.44 | 7.42 | 1.99 | 0.28/45 | 0.001 | " | 0.35/55 |
| 120–135 | 0.34 | 8.00 | 1.60 | 0.64/50 | 0.006 | " | 0.63/50 |
| Solonchak over the meadow soil, pit 53 | | | | | | | |
| 4–20 | 2.85 | 7.80 | 0.66 | 0.20/30 | 0.001 | 0.01/1 | 0.45/69 |
| 20–40 | 2.02 | 7.50 | 0.68 | 0.43/63 | 0.001 | Absent | 0.25/37 |
| 40–60 | 1.50 | 8.10 | 0.71 | 0.29/40 | 0.003 | " | 0.46/60 |
| 90–120 | 0.24 | 8.25 | 0.70 | 0.56/51 | 0.007 | " | 0.33/47 |
| 120–160 | 0.19 | 7.90 | 0.66 | 0.46/70 | 0.003 | " | 0.20/30 |

* Above the line is cmol(equiv)/kg; under the line is % of the Alk total.

Alk total is titrated alkalinity, Alk carb is carbonate alkalinity, Alk bor is borate alkalinity, Alk org is alkalinity of anions of organic acids. The analyses were performed by S.P. Zamana using the method of Vorob'eva and Zamana [8, 9].

cisely these soils of Mongolia to the category of soda–chloride–sulfate soils, i.e. to the same province of salt accumulation as the soils of Xinjiang were referred.

The authors studying saline soils of the Mongolian oases paid attention to some discrepancy in the contents of pH, and water-soluble calcium. Previously, Egorov noted this fact as well for the soils of Xinjiang. Therefore, we decided to consider the nature of alkalinity in the soils studied more thoroughly.

Vorob'eva and Zamana [8, 9, 31] studied the nature of alkalinity in the soils and waters of Ekhiin-Gol using our samples. The results of the investigations showed a complicated structure of the alkalinity in the solonchaks of the oasis. The alkalinity of water extracts from the oasis soils may be determined by carbonates, borates, and anions of organic acid salts (Table 9). In the waters, the borate alkalinity often exceeds the toxic level (1 mg/L) [40, 41]. Nowadays, the problem of the nature of alkalinity in the soils of Central Asian oases has not been solved yet; it needs further research.

## CONCLUSIONS

(1) The current salt accumulation is manifested in the soils of Gobi deserts at the groundwater table deeper than 1.5–3.0 m, except for the soils, on the surface of which flood ice (naleds) are formed in winter. When thawing, these naleds provide leaching of the dark-colored meadow soils.

(2) The salt accumulation in the soils at the water exchange of $\bar{V} > 1$ is observed even under extremely low (up to 1.0–1.5 g/L) mineralization of groundwater.

(3) The process of current salt accumulation in the soils of the Gobi oases is associated with the predominance of the annual evaporation over the ingress of water to the soil surface. The current salt accumulation determines the formation of a solonchak's profile, with the maximum of salts (to 40–60%) in the upper 30-cm-thick layer.

(4) In the upper horizons of the oasis solonchaks, salt crusts are formed; the lower part of the soil profiles remains practically nonsaline. This is related to a unidirectional movement of salts to the upper soil layers during the year and to the absence of even periodical wetting of the soils in the precipitation period because of its minor amount.

(5) The salt composition of the solonchaks is determined by the composition of the groundwater and metamorphization of salts under freezing. The soils with chloride–sulfate–sodium salinization, sometimes with elevated alkalinity, prevail.

(6) In the sulfate solonchaks of the oases, various minerals of sulfate–sodium salts are present: mirabilite, thenardite, and glauberite. Mirabilite predominates due to a weak heating of the soils and crystallization of salts at low temperatures, characteristic of continental deserts of Mongolia.

(7) A specific feature of the oasis solonchaks in Mongolia is the elevated alkalinity in the saline horizons at the high content of neutral salts, which can be determined by different compounds: carbonates of alkaline and alkaline-earth elements, borates and anions of organic compounds.

**Table 9.** Water-soluble boron and borate alkalinity in soils of the Ekhiin-Gol oasis [31]

| Depth, cm | Boron, mg/kg | Alk bor, cmol(equiv)/kg |
|---|---|---|
| | Solonchak, pit 4 | |
| 0–2 | 27.00 | 0.06 |
| 2–7 | 12.96 | 0.02 |
| 7–12 | 23.76 | 0.05 |
| 12–25 | 19.44 | 0.04 |
| 25–50 | 21.00 | 0.03 |
| 50–85 | 8.64 | 0.01 |
| | Solonchak, pit 46 | |
| 0–3 | 72.36 | 0.24 |
| 3–10 | 388.80 | 1.70 |
| 10–20 | 317.52 | 1.30 |
| 20–40 | 23.76 | 0.04 |
| 40–80 | 10.80 | 0.01 |
| | Solonchak, pit 17A | |
| 0–2 | 17.72 | 0.20 |
| 2–15 | 87.48 | 0.10 |
| 15–30 | 110.16 | 0.20 |
| 30–60 | 43.20 | 0.03 |
| 80–90 | Absent | |
| 90–120 | " | |

The analyses were performed by S.P. Zamana (Lomonosov Moscow State University) using potentiometric titration with mannite.

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