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SALINITY OF SOILS OF THE DRIED-UP BOTTOM OF THE ARAL SEA

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Annotation. This study investigates the physico-chemical stratification and salinity dynamics of residual–marshy soils formed on the dried bed of the Aral Sea. Field investigations were conducted at experimental plots located in the Aral Lowland (“0” point), covering a soil profile depth of 0–200 cm. The results reveal a pronounced vertical heterogeneity in salt distribution, with moderate to strong salinity prevailing within the 0–45 cm layer. The dominant salinity types are chloride–sulfate and magnesium–sodium. Maximum accumulation of dry residue and soluble salts was observed in the 0–2 cm and 22–29 cm horizons, which is attributed to intense surface evaporation and capillary rise of shallow groundwater. The exchangeable cation composition is dominated by Mg^{2+} and Na^{+}, indicating hydromorphic soil formation conditions. The findings provide valuable insights into soil degradation processes and serve as a scientific basis for developing effective reclamation and land restoration strategies in the dried Aral Sea region.

Key words: Aral Sea, residual-marshy soils, soil salinity, ion distribution, land degradation.

Аннотация. В статье представлены результаты исследований физико-химической стратификации и динамики засоления остаточно-болотных почв высохшего дна Аральского моря. Исследования проведены на экспериментальных участках Аральской низменности («точка 0») по профилю 0–200 см. Установлено, что распределение солей по вертикали отличается выраженной неоднородностью: в слое 0–45 см преобладает среднее и сильное засоление хлоридно-сульфатного и магниево-натриевого типа. Максимальное накопление сухого остатка и легкорастворимых солей отмечено в слоях 0–2 см и 22–29 см, что связано с процессами испарения и капиллярного подъема грунтовых вод. В составе поглощающего комплекса доминируют Mg^{2+} и Na^{+}, что отражает гидроморфный характер почвообразования. Полученные результаты имеют важное значение для оценки деградации почв и разработки научно обоснованных мер по рекультивации засоленных земель высохшего дна Аральского моря.

Ключевые слова: Аральское море, остаточно-болотные почвы, засоление, ионный состав, деградация почв.

Annotatasiya. Ushbu tadqiqot Orol dengizining qurigan tubida shakllangan qoldiq–botqoq tuproqlarning fizik-kimyoviy qatlamlanishi va sho‘rlanish dinamikasini baholashga bag‘ishlangan. Tadqiqotlar Orolbo‘yi pasttekisligining “0” nuqtasida joylashgan tajriba maydonlarida 0–200 sm chuqurlik bo‘yicha olib borildi. Natijalar tuproq profilida tuzlarning notekis taqsimlanganligini ko‘rsatdi: 0–45 sm qatlamda o‘rtacha va kuchli sho‘rlanish ustun bo‘lib, sho‘rlanish turi asosan xlorid–sulfat va magniy–natriy xususiyatiga ega. Quruq qoldiq va eruvchan ionlarning maksimal to‘planishi 0–2 sm hamda 22–29 sm qatlamlarda qayd etildi, bu bug‘lanish va grunt suvlari kapillyar ko‘tarilishi bilan izohlanadi. Almashinuvchi kationlar tarkibida Mg^{2+} va Na^{+} ustunligi tuproqning gidromorf sharoitda shakllanganligini ko‘rsatadi. Olingan natijalar Orol dengizi qurigan tubida tuproq degradatsiyasini baholash va rekultivatsiya choralarini ishlab chiqishda muhim ilmiy ahamiyatga ega.

Kalit so‘zlar: Orol dengizi, qoldiq-botqoq tuproqlar, sho‘rlanish, ionlar taqsimoti, tuproq degradatsiyasi.

Intarduction. The Aral Sea region has undergone profound environmental changes over the past decades, primarily due to anthropogenic water withdrawals and climatic variations[1]. highlighted the dynamics of vegetation in the Aral Sea coast, noting significant shifts in plant communities as a result of both natural and anthropogenic factors. The study emphasized that these changes have led to a decline in biodiversity and alterations in ecosystem services. Similarly [2], demonstrated the potential of combining soil data with remote-sensing information to detect salinity hazards in semi-arid regions, underscoring the importance of integrated monitoring for sustainable land management [3].Provided comprehensive remote sensing and ground-based analyses of the dried Aral Sea bed, revealing extensive soil salinization and degradation processes. According to [4], accurate agricultural data are critical for assessing soil quality and guiding mitigation strategies in such degraded areas [5]. employed optical Sentinel-2 imagery and nonlinear regression models to estimate soil salinity in the dried bed of Urmia Lake, which parallels the challenges observed in the Aral Sea Basin [6]. Modeled irrigated cotton production under shallow groundwater conditions in the Aral Sea Basin, illustrating how soil salinity dynamics can influence crop yields [7]. Examined aridity indices in Southern Italy, providing a methodological framework that can be applied to arid regions like Central Asia. Similarly, global datasets on precipitation and evapotranspiration, as compiled by [8], offer crucial insights into drought and desertification trends relevant to the Aral Sea [9]. Further corroborated the extensive degradation of the Aral Sea bed through combined remote and ground studies, emphasizing the need for sustainable restoration measures [10]. Analyzed temporal and spatial changes in temperature and precipitation in Central Asia, highlighting significant climatic pressures on water resources and soil quality [11]. Proposed bias-correction techniques for aridity index simulations, enhancing the accuracy of climate model projections for dryland regions [12]. Investigated the impact of plantation development on biological soil crusts and topsoil properties in northern China, which can inform rehabilitation strategies for degraded soils in the Aral region[13]. Studied the differential response of soil microbes and endophytes to geochemical changes, highlighting the importance of microbial monitoring in environmental assessments[14]. Documented temperature changes in Central Asia between 1979 and 2011, reinforcing the observed trends of regional warming and its implications for soil salinization[15]. Evaluated the potential cooling effect of Aral Sea restoration, demonstrating the

interconnection between hydrological interventions and local climate moderation [16]. Combined remote sensing and modeling approaches to assess soil salinity in irrigated areas, offering practical guidance for sustainable agriculture in the basin [17,18]. Documented dust and sand transport across the Aral Sea region, underscoring the ecological consequences of land desiccation [19]. Explored remediation techniques and biochar applications in degraded soils, suggesting feasible approaches to restore soil health in saline-affected areas[21]. Analyzed changes in soil properties and enzyme activities along afforestation gradients on the dry Aral Sea bed, demonstrating positive effects of vegetation restoration [22]. Provided an overview of historical and current ecological conditions in the Aral region, emphasizing long-term environmental degradation [23]. Assessed irrigated land salinization, illustrating the critical interplay between agricultural practices and soil degradation [24]. Analyzed drought dynamics in Central Asia using GRACE data, confirming widespread water stress and its implications for regional soils[25]. Proposed a remote sensing-based approach for hydro-saline land degradation assessment, reinforcing the role of geospatial techniques in monitoring[26]. Studied the effect of biopreparations on cotton under salinization, highlighting practical interventions to mitigate soil stress [27]. Documented glacier changes in the Eastern Pamir, indirectly affecting water availability and soil conditions downstream [28]. Identified potential vegetation establishment areas on the dried Aral Sea floor using satellite imagery, contributing to restoration planning. Provided foundational knowledge on heavy metal uptake and soil interactions, relevant to contaminated sites. Examined human vulnerability to climate change in the Aral Sea Basin, emphasizing socio-environmental feedbacks utilized satellite monitoring to assess large-scale water storage depletion, directly linking hydrological changes to soil degradation mapped cropland abandonment in the basin, illustrating land-use changes as a driver of ecological transformation. Finally, evaluated the impact of soil nutrient medium on crop yields, demonstrating the agricultural significance of soil restoration in the Aral Sea region. These studies collectively underscore the complex interactions between climate, hydrology, soil salinization, vegetation dynamics, and human interventions in the Aral Sea Basin. Integrated monitoring, remote sensing, and sustainable management practices are essential for mitigating environmental degradation and promoting ecosystem recovery.

1. Result

1.1 Residue Content and Salinity

In the “0” point residual-marshy soils of the Aral region, studied on 0–10 ha plots, the dry residue content ranged from 4.835% to 1.979%, progressively decreasing with increasing soil depth. The highest accumulation of dry residue was observed in the 0–2 cm and 22–29 cm layers, whereas deeper horizons contained lower amounts, ranging from 0.61% to 1.91%. This vertical pattern indicates that organic matter is primarily concentrated in the surface and intermediate horizons, likely reflecting the combined effects of plant litter deposition and limited decomposition under marshy conditions.

1.2. Carbonates and Salinity Indices

The concentration of bicarbonates (HCO_3^-) was low, fluctuating between 0.003% and 0.015%, suggesting minimal carbonate accumulation in these soils. The chloro-sulfate index (CI) ranged from 0.390% to 0.900%, while sulfate ion (SO_4^{2-}) content decreased from 2.850% to 0.860% with depth. Calcium (Ca^{2+}) concentrations varied between 0.453% and 0.185%, magnesium (Mg^{2+}) ranged from 0.597% to 0.140%, and sodium (Na^+) remained relatively constant between 0.013% and 0.019%.This ion composition characterizes the soils as chloride-sulfate type salinized,

ranging from moderately to highly saline in the 0–45 cm soil layer. Such vertical distribution of soluble salts is consistent with patterns commonly observed in marshy soils under arid and semi-arid conditions, influenced by capillary rise and evaporation.

1.3. Chloride and Sulfate Ions

Chloride (Cl^-) concentrations fluctuated between 0.27% and 1.18% across soil horizons, whereas sulfate (SO_4^{2-}) varied from 0.120% to 0.480%, with maxima recorded in the 0–2 cm and 22–29 cm layers. These trends indicate that soluble salts accumulate primarily in the surface and near-intermediate horizons, likely as a result of evaporation and shallow groundwater dynamics.

1.4. Calcium and Magnesium Ions

Calcium (Ca^{2+}) ions were highest in the 0–2 cm and 2–6 cm layers, while deeper horizons showed markedly lower concentrations (0.010% to 0.160%). Magnesium (Mg^{2+}) exhibited a decreasing trend with depth. This pattern is typical of marshy saline soils, where soluble cations accumulate in the upper horizons due to surface salinization and limited leaching in waterlogged conditions. The residual-marshy soils of the Aral Lowland "0" point and Moynaq district were analyzed for residue content. In the upper layers (0–2 cm), residue content ranged from 2.69% to 43.00%, while in deeper horizons it decreased to 0.49–1.91% (Pic.1).

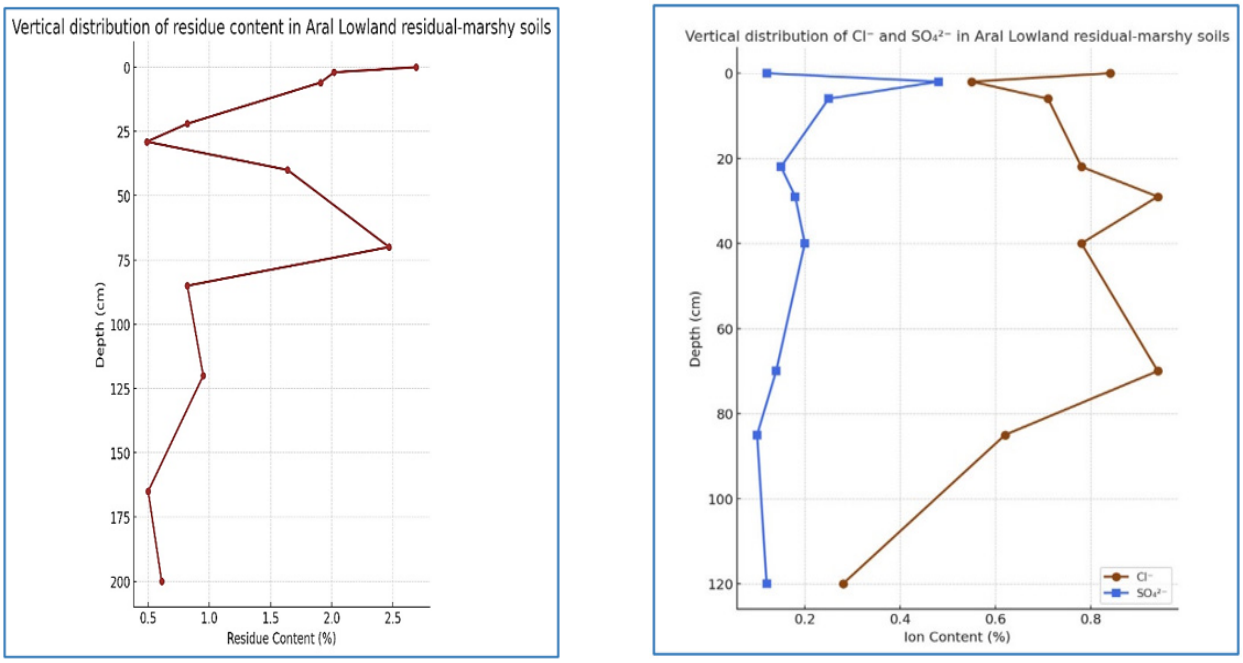


Figure 2. Vertical distribution of Cl^- and SO_4^{2-} ions (%)

The observed vertical distributions of dry residue and soluble ions in the residual-marshy soils of the Aral region demonstrate moderate to strong salinization within the 0–45 cm layer, predominantly of the chloride-sulfate type. The dual peaks in residue and salt content at 0–2 cm and 22–29 cm indicate layered accumulation resulting from:

· Surface evaporation, leading to salt and organic matter concentration in the topsoil.

· Capillary rise from shallow groundwater, promoting accumulation in intermediate horizons.

· Negligible carbonate formation, characteristic of marshy and waterlogged conditions.These findings are essential for understanding soil fertility and salinity dynamics in degraded marshy soils of the Aral Sea region. They suggest that effective soil reclamation strategies, including leaching or amendment applications, may be necessary to mitigate salinity in

the upper horizons and improve agricultural potential. The higher residue content in the upper layers indicates organic matter accumulation. The decrease with depth correlates with increased salinity and ion concentration.

2. Salinity Chemistry

The salinity types in Aral Lowland "0" point soils were as follows:

· Upper layers: chloride-sulfate, slightly saline.

· Lower layers: chloride, sulfate-chloride, moderately to strongly saline.

• **Discussion:** Chloride dominates in the upper layers, while lower layers contain a mixed sulfate-chloride salinity, reflecting the soil's hydromorphic characteristics. Magnesium ions (Mg^{2+}) in the studied layers ranged from 0.12% to 0.13% in the upper horizons, whereas in the lower horizons their concentration decreased to between 0.006% and 0.03%. Sodium ions (Na^{+}) did not exhibit a clear distribution pattern across the soil profile. Specifically, in the 6–22 cm, 40–70 cm, and 85–120 cm layers, Na^{+} concentrations varied between 0.08% and 0.14%, while in other horizons, chloride ion (Cl^{-}) content was relatively high, ranging from 0.28% to 0.62%.

3. Exchangeable Cations

The distribution of exchangeable cations in 0–120 cm layers is summarized as follows:

Ion	Upper Layer (%)	Lower Layer (%)	**Notes**
Ca^{2+}	26.1–61.6	1.4–8.0	**Supports soil structure in upper horizons**
Mg^{2+}	35.4–72.2	6–49	**Dominant with Na^{+}**
K^{+}	0–0.1	0.1–0.9	**Very low**
Na^{+}	1.2–2.9	27–86.5	**High in lower horizons**

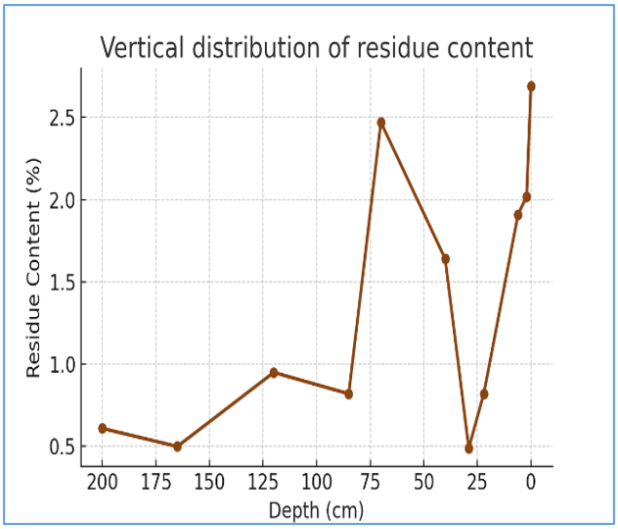


Figure 3. Vertical distribution of exchangeable cations (mg/eq) in residual-marshy soils

Mg^{2+} and Na^{+} dominate the soil's exchange complex, while Ca^{2+} is concentrated in upper layers supporting soil structure. K^{+} plays a minor role.The vertical variation reflects salinity and hydromorphic processes. The elevated chloride levels in certain horizons suggest localized salt accumulation, which may be influenced by capillary rise, evaporation, and shallow groundwater interactions. These results indicate that Mg^{2+} is concentrated in the surface layers, likely due to limited leaching and evapoconcentration, whereas Na^{+}distribution is irregular, reflecting the complex dynamics of soluble salts in marshy saline soils.

Conclusions

Based on the comprehensive experimental studies conducted on the dried bed of the Aral Sea, the following conclusions can be drawn: Heterogeneous Soil Salinity: The semi-consolidated sandy desert–salt marsh soils of the Aral Sea's dried bed exhibit non-uniform salt distribution across vertical layers. In the first experimental plot, moderate salinity was observed in the 0–22 cm layer, weak salinity in the 22–145 cm layer, and moderate salinity in the 145–200 cm layer, predominantly of magnesium-sodium type. In the second

plot, strong salinity extended uniformly across the 0–155 cm profile, primarily of calcium-magnesium type. Variable Accumulation of Toxic Salts: The accumulation and vertical distribution of toxic salts do not follow a consistent pattern. In the first experimental site, salt concentration peaked in the 0–2 cm layer, decreased between 2–150 cm, and increased again at 150–200 cm. In the second site, salts were evenly distributed throughout the 0–155 cm profile.

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