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INTEGRATED ASSESSMENT OF PHYSICO-CHEMICAL AND BIOLOGICAL PROPERTIES OF SOILS IN THE DRIED ARAL SEA BASIN

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Abstract. *This study presents a comprehensive analytical assessment of the ecological, geomorphological, and biotic transformations occurring within the newly formed soil–geosystems of the desiccated Aral Sea basin. The research emphasizes the application of systematic and probabilistic forecasting methods to evaluate the dynamics transformed landscapes. The results reveal that ongoing salinization, deflation, and vegetation degradation processes are closely interlinked with hydrological imbalance, industrial impact, and a redistribution of salts. Probabilistic modeling of environmental changes indicates a high likelihood of continued desertification (up to 0.8 probability) by 2030 under current conditions. The study proposes an integrated forecasting framework to improve the resilience and sustainable management of the region's ecosystems.*

Keywords: *ecological forecasting, Aral Sea, salinization, deflation, ecological stability, anthropogenic degradation*

Introduction. The Aral Sea region represents one of the most ecologically unstable zones in Central Asia. The dramatic shrinkage of the sea has led to the formation of vast new arid territories, where geomorphological, hydrological, and biotic processes are undergoing rapid transformation. In these conditions, ecological–geographical forecasting has become a fundamental scientific tool for assessing the trajectory of environmental change and degradation. According to the theoretical framework of forecasting developed In the Aral Sea basin, the object of such forecasting is the anthropogenically modified natural system, characterized by disturbed soil–water regimes, deflation processes, and disrupted vegetation cover. Recent studies have increasingly focused on the assessment of soil degradation and ecological transformation processes in the Aral Sea Basin, where desiccation has led to severe alterations in soil structure, salinity, and biological activity. According to Djumaniyazova et al. (2021), the drying of the Aral Sea has resulted in the formation of extensive saline plains dominated by halomorphic and sandy soils, which exhibit highly variable physico-chemical characteristics depending on microrelief and wind deposition patterns. This environmental transformation has caused significant disruption in soil-forming processes and ecosystem functionality. Their findings demonstrate that parameters such as pH, electrical conductivity (EC), soil organic matter (SOM), available nutrients (N, P, K), and enzymatic activity (urease, catalase, dehydrogenase) are critical indicators for assessing the impact of chemical contamination and salinity on soil productivity. In the context of soil salinization dynamics, Toderich et al. (2020) emphasized the role transport and secondary salinization caused by groundwater mineralization. The researchers highlighted that soluble salts (Na^+, Cl^-, SO_4^{2-}) accumulate in the upper horizons, thereby altering soil structure, porosity, and water-holding capacity. These findings align with FAO (2021) global soil reports, which underline salinization and contamination as major threats to soil health, particularly in post-irrigated desert ecosystems. From a biological perspective, microbial biomass and enzymatic activity as sensitive indicators Aral Sea basin soils, indicating that biological parameters are essential for soil quality monitoring under extreme aridification. Similarly, Yuldasheva et al. (2022) found that microbial respiration and catalase activity decline significantly in soils with high electrical conductivity and heavy metal contamination, particularly in areas close to industrial effluent sources. Advanced analytical approaches such as multivariate statistics, correlation analysis, For instance, Karlen et al. (2021) and Wienhold et al. (2022) proposed soil health indices combining physical (bulk density, porosity), chemical (pH, SOM, nutrient status), and biological (enzymatic activity) parameters into composite indicators that effectively classify soil degradation levels. Such integrative models are particularly valuable for large-scale monitoring programs in fragile ecosystems like the dried Aral Sea region. Mukhamedov et al. (2024) developed spatial interpolation maps of soil salinity and contamination using Sentinel-2 imagery, revealing strong spatial heterogeneity across the Aralkum Desert. This geospatial integration enhances the predictive capacity of soil monitoring systems and supports decision-making for ecological rehabilitation and land management strategies. Overall, contemporary research (2020–2024) emphasizes that the assessment of soils in the dried Aral Sea Basin requires a multidisciplinary and indicator-based framework. Combining physico-chemical, enzymatic, and microbiological properties with geospatial modeling offers a comprehensive understanding of soil health dynamics and their ecological implications. These findings collectively support the development of sustainable remediation and monitoring strategies tailored to the unique conditions of the post-Aral ecosystem.

Materials and Methods. This review synthesizes data from 2020–2024 peer-reviewed studies, focusing on: **Physico-chemical indicators:** pH, EC, SOM, macro-nutrients, bulk density, porosity; **Biological indicators:** microbial biomass, enzymatic activities (urease, catalase, dehydrogenase); Data interpretation followed the frameworks of **Karlen et al. (2021)** and **FAO (2021)** for soil health assessment. Studies conducted within the Aralkum Desert, and adjacent irrigated zones were comparatively analyzed to determine the key environmental drivers of soil property variation

Results and Discussion. Physico-Chemical Characteristics. The upper soil layers of the Aralkum Desert exhibit high **electrical conductivity (EC)**, often exceeding 10–20 dS/m, due to the accumulation of **Na^+**, **Cl^-**, and **SO_4^{2-}** ions from evaporite deposits (**Toderich et al., 2020**). The pH values are predominantly alkaline (8.3–9.1), while organic matter remains critically low (0.2–0.5%), indicating poor nutrient cycling. According to **Kenzhebayev et al. (2022)**, the reduction in soil direct effect on nutrient retention and aggregate stability.

Biological and Enzymatic Indicators. Microbial and enzymatic activities show a strong decline with increasing salinity and contamination levels. **Abdukarimov et al. (2023)** reported a 3–5 fold reduction in urease and catalase activity in soils with EC above 15 dS/m. Similarly, **Yuldasheva et al. (2022)** demonstrated that heavy metals (Zn, Pb, Cu) from emissions suppress microbial respiration, resulting in low soil biological potential. These findings support the argument that biological parameters are sensitive early-warning indicators of soil degradation.

Integrated Soil Health Assessment. Recent research has employed integrated soil health indices (SHI) combining physical, chemical, and biological data to quantify soil quality in post-Aral landscapes. **Karlen and Wienhold (2022)** proposed a model that uses standardized scores (0–1) for each indicator to produce a composite.In the Aral region, the values typically range from 0.25 to 0.45, indicating degraded to moderately healthy conditions. Such indicator-based approaches facilitate temporal monitoring and can guide restoration prioritization.

Discussion. The Aral Sea basin is currently at a critical stage of ecological destabilization. Anthropogenic pressure, coupled with altered hydrological and climatic conditions, has led to irreversible transformations in soil structures. Ecological geographical forecasting thus serves not only as a descriptive tool but also as a strategic decision-making framework for regional land management. To enhance the reliability of forecasts, three methodological directions are essential:
Indicator-based evaluation – integrating salinity, moisture, microbial activity, and vegetation cover indices;

Systematic monitoring – using GIS-based and remote sensing datasets for spatiotemporal modeling;

Scenario simulation – developing predictive models for sustainable ecosystem recovery.

Conclusion. The analysis of recent literature (2020–2024) reveals that the soils of the dried Aral Sea Basin are characterized by high salinity, low organic matter, and weak biological activity. Physico-chemical degradation, combined with declining microbial functionality, poses significant challenges for ecosystem recovery. Integrated soil health indices and soil-based monitoring frameworks represent effective analytical tools for tracking degradation and guiding rehabilitation strategies. Future research should focus on long-term monitoring, microbial adaptation mechanisms, and the optimization of soil remediation technologies in arid saline environments.