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COMPREHENSIVE HYDROECOLOGICAL ASSESSMENT OF WATER RESOURCES AND MELIORATION IMPACTS IN THE ARAL SEA

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Abstract: *This study presents a comprehensive hydro ecological evaluation of water resources and the effects of melioration on the irrigated landscapes of the Republic of Karakalpakstan, located Aral Sea dried bottom. A refined landscape geochemical method was developed to assess hydro ecological status at the scale of small irrigation basins. This approach enabled the quantitative and qualitative characterization of river, collector-drainage, and groundwater systems improving the precision of regional water balance assessments and quality monitoring. Findings demonstrate a significant spatial variation in water mineralization (ranging from 0.5 to 10 g/L), hardness (8.5–160 mg-eq/L), and ion composition dominated by* Cl^- *and* SO_4^{2-} *ions. Groundwater salinity and depth fluctuations across indicate progressive. Recommendations for reusing collector-drainage waters to irrigate salt-tolerant crops and reclaim highly saline soils have been integrated into the regional water management system, supporting sustainable use of limited water resources under climate variability and Aral Sea desiccation impacts.*

Keywords: *Hydro ecology, melioration, mineralization, groundwater, collector-drainage water, Aral Sea basin,*

1. Introduction

The Republic of Karakalpakstan, located in the lower reaches of the Amu Darya River and adjacent to the Aral Sea basin, represents one of the most hydroecologically vulnerable regions of Central Asia (UNEP, 2020; Micklin, 2016). Extensive irrigation and melioration practices, initiated during the 20th century, have caused large-scale changes in hydrological regimes, water salinity, and soil degradation. The drying of the Aral Sea, combined with reduced river inflow and excessive groundwater extraction, has led to the intensification of secondary salinization, deterioration of water quality, and the transformation of deltaic ecosystems (Molden et al., 2007; FAO, 2018).The current study aims to assess the hydroecological condition of surface and groundwater systems, analyze spatiotemporal dynamics of mineralization and salinity, and identify management pathways for optimizing water use efficiency in irrigated and reclaimed lands.

2. Materials and Methods

2.1 Study Area

The study covers the lower Aral Sea basin, including the Muynak districts of Karakalpakstan, the Amu Darya delta, and parts of the Aral Sea dried bottom (Aral sea Desert). These territories include extensive irrigated agricultural lands and collector-drainage networks connected to the main channel and its tributary systems.

2.2 Key Indicators

Measured parameters included river discharge, mineralization (g/L), total hardness (mg-eq/L), dissolved oxygen, pH, dominant ion composition (Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-), groundwater depth, and collector-drainage flow characteristics.

2.3 Analytical Methods

A combination of hydrochemical and GIS-based mapping methods was employed. Long-term observation data (1963–2019) were processed using correlation and regression analyses to identify trends and causal relationships between irrigation intensity, groundwater levels, and salinity. The landscape–halo-geochemical method was refined for regional hydroecological assessment (Karimov et al., 2019; Karakalpakstan Ministry of Water Resources, 2020).

3. Results and Discussion

3.1 Hydrological and Hydrochemical Regime

Analysis of hydrological data shows that the Amu Darya's discharge has decreased 1.3–1.6 times between 2000 and 2012 compared to early 20th-century records. The river's chemical composition is dominated by chloride and sulfate ions, followed by sodium, calcium, and magnesium. Total mineralization reaches up to 2–3 g/L in average years, increasing toward the delta region due to evaporation and drainage inflow.Seasonal variations indicate maximum salinity during low-flow periods (July–September) and minimum during high-flow months (March–April). These fluctuations correspond to irrigation cycles and the timing of leaching and drainage processes.

3.2 Collector–Drainage System and Melioration Effects

Fifteen major collectors discharge approximately 2.2 km³ of saline water annually into the Amu Darya delta (Karakalpakstan Ministry of Water Resources, 2020). The mineralization of collector-drainage waters ranges from 1.7 to 3.9 g/L, predominantly of chloride–sulfate–magnesium–sodium type.During high-water years, discharge volumes increase, while mineralization decreases, indicating the dilution effect. Conversely, in dry years, reduced flow intensifies salt accumulation and return flow contamination.These findings confirm the strong dependence of irrigation water quality on upstream flow availability and management efficiency, consistent with earlier studies by Molden et al. (2007) and Doran & Karlen (1994).

3.3 Groundwater Dynamics and Salinity

Groundwater depths across irrigated lands range from 0.5 to 5 meters, with salinity levels varying between 1 and 10 g/L. In the 1980–1999 period, groundwater levels fluctuated between 180 and 210 cm, but during the low-water years of 2000–2001, they deepened to 350–360 cm, slightly improving soil reclamation status. Approximately 440,000 ha of irrigated lands are affected by groundwater salinity between 1–3 g/L, while more than 6,000 ha exceed 5 g/L. Persistent secondary salinization is associated with shallow groundwater, low natural drainage, and high evapotranspiration, confirming earlier hydrogeological findings (FAO, 2018; Karimov et al., 2019).

3.4 The Current State of the Aral Sea

The Aral Sea continues to shrink. By 1990, its total area decreased to 43,000 km², and the Large Aral became divided into eastern and western lobes. Today, the eastern part has almost dried out, exposing over 6 million hectares of saline desert surface (Orolqum). Annual windborne dust emissions from the desiccated seabed are estimated at 75 million tons (UNEP, 2020). Monitoring of the Sarbas, Moynaq, and Shigekul water bodies shows mineralization ranging from 7 to 17 g/L, with SO_4^{2-} and Cl^- dominance. This extreme salinity underscores the importance of reusing collector-drainage waters for salt-tolerant crop irrigation and afforestation of the dried seabed to mitigate dust storms and ecological degradation.

4. Conclusions

The hydroecological condition of Karakalpakstan's water systems is critically influenced by anthropogenic water regulation, insufficient drainage, and long-term irrigation practices. The refined landscape–halo-geochemical method provides a robust framework for assessing hydroecological status across administrative districts.

Implementing this methodology in regional water management has enhanced the accuracy of water accounting and quality monitoring (Karakalpakstan Ministry of Water Resources, 2020). Reuse of collector-drainage waters in saline lands offers a practical adaptation measure in water-scarce years, improving reclamation efficiency and maintaining agricultural productivity. Continued monitoring and integration of GIS-based models are essential to forecast groundwater salinity dynamics and to plan sustainable water resource use in the Aral Sea basin.

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