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The Assessment of Groundwater Influence on Soil Fertility in The Republic of Karakalpakstan (Southern, Central and Northern Districts)

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Abstract: This article examines the influence of groundwater on soil fertility in the Republic of Karakalpakstan, with a comparative focus on the southern (Beruniy, Turtkul), central (Nukus, Kegeyli), and northern (Muynak, Kungrad) districts. The research analyzes groundwater depth, mineralization, and their relationship with soil salinity, humus content, and nutrient availability. The results indicate that shallow and highly mineralized groundwater significantly contributes to secondary salinization, degradation of soil structure, and reduction of agricultural productivity, especially in northern districts affected by the Aral Sea ecological crisis. In contrast, deeper and less mineralized groundwater in southern areas supports relatively stable soil fertility conditions. The study highlights the necessity of integrated groundwater management, improved drainage systems, and water-saving irrigation technologies to ensure sustainable land use and ecological stability in Karakalpakstan.

Keywords: Groundwater, soil fertility, salinity, Karakalpakstan, irrigated soils, mineralization, Aral Sea crisis, land degradation, hydrogeology, sustainable agriculture.

Introduction: The Republic of Karakalpakstan represents one of the most ecologically sensitive territories of Central Asia. Located within the lower reaches of the Amu Darya River basin, the region has experienced significant environmental transformations during the last several decades [2]. The desiccation of the Aral Sea, increasing aridity, water scarcity, and irrational irrigation practices have drastically changed soil and groundwater conditions. Groundwater plays a dual role in arid agricultural systems. On the one hand, it may provide additional moisture for crops through capillary rise. On the other hand, shallow and mineralized groundwater contributes to soil salinization and land degradation [8, 21-26]. Therefore, the relationship between groundwater and soil fertility remains one of the key research directions in modern soil science and land reclamation studies [9, 180-184]. The hydrogeological conditions of Karakalpakstan differ considerably among southern, central, and northern districts. Southern territories are relatively more favorable due to better irrigation infrastructure and lower groundwater salinity. Central districts are characterized by transitional conditions, whereas northern districts experience severe ecological stress because of the direct impact of the Aral Sea crisis [5, 1-15].

Special attention to the rational use of water resources and improvement of the meliorative condition of irrigated lands has also been emphasized in the state policy of the Republic of Uzbekistan. In particular, the Resolution of the President of the Republic of Uzbekistan No. RP-4912, dated December 5, 2020, “On Urgent Measures for the Effective Use of Water Resources and the Improvement of the Meliorative Condition of Lands in the Republic of Karakalpakstan,” identified serious problems related to groundwater rise, insufficient drainage systems, and increasing soil salinity in the region.. The decree highlighted the necessity of introducing water-saving technologies, modernizing irrigation infrastructure, and improving the ecological condition of irrigated lands. These governmental reforms further increase the scientific significance of studying groundwater influence on soil fertility in Karakalpakstan [1].

Numerous scientists have investigated salinization processes, groundwater dynamics, and irrigated soil degradation in Central Asia. However, comprehensive comparative researchs focused specifically on the territorial differentiation of groundwater influence in Karakalpakstan remain limited [7, 17-20]. Consequently, this research article aims to systematize and analyze scientific findings related to groundwater impacts on soil fertility across different regions of the republic.

METHODOLOGY

This research was carried out through comparative and analytical methods in order to evaluate the influence of groundwater on soil fertility in the Republic of Karakalpakstan. First of all, scientific articles, hydrogeological reports, environmental studies, and statistical materials related to groundwater and soil salinity were collected from national and international sources. Subsequently, the obtained information was systematically classified according to the southern, central, and northern districts of Karakalpakstan. Furthermore, special attention was paid to the analysis of groundwater depth, mineralization level, soil salinity, humus content, and nutrient availability. In addition, comparative analysis was used to identify similarities and differences among the studied regions. At the same time, descriptive and interpretative approaches helped explain the relationship between groundwater conditions and soil degradation processes. Moreover, scientific findings associated with irrigation practices, collector-drainage systems, and the ecological consequences of the Aral Sea crisis were critically examined. Consequently, the role of shallow and highly mineralized groundwater in the formation of saline soils was identified. Finally, all collected scientific data were generalized and synthesized to develop conclusions regarding sustainable groundwater management and preservation of soil fertility. Therefore, the methodology combined literature research, comparative assessment, and interdisciplinary environmental analysis.

RESULTS

The results of the study demonstrated considerable regional differences in groundwater conditions and their influence on soil fertility within the Republic of Karakalpakstan. In particular, groundwater depth, mineralization level, and salinity intensity varied significantly between the southern, central, and northern districts. Consequently, these differences directly affected soil productivity, humus accumulation, nutrient availability, and ecological stability.

First of all, the southern districts, especially Beruniy and Turtkul districts, showed comparatively favorable hydrogeological and agroecological conditions. In these territories, groundwater levels were generally located at depths between 2.5 and 4.0 meters. At the same time, groundwater mineralization remained relatively low, averaging 2–4 g/L. Therefore, capillary salt movement toward the soil surface was less intensive. Moreover, collector-drainage systems in southern irrigated areas functioned more effectively compared to other regions. As a result, soils retained comparatively stable fertility indicators and lower salinity levels.

Furthermore, humus accumulation in Beruniy and Turtkul districts ranged between 1.1% and 1.5%, indicating relatively favorable biological activity and organic matter circulation. In addition, nitrogen and phosphorus availability remained at satisfactory levels for agricultural production. Consequently, these conditions supported more stable crop yields and reduced risks of land degradation.

In contrast, the central districts, particularly Nukus and Kegeyli districts, demonstrated transitional hydrogeological characteristics. Groundwater depth fluctuated between 1.5 and 3.0 meters, while mineralization levels increased to 5–8 g/L. Therefore, moderate salinization processes became widespread in irrigated lands. Moreover, excessive irrigation and insufficient drainage accelerated the accumulation of soluble salts in upper soil horizons.

Additionally, humus content in Nukus and Kegeyli districts decreased to approximately 0.8–1.1%, which reflected moderate deterioration of soil biological activity. Simultaneously, soil structure gradually worsened because saline conditions reduced permeability and aeration. As a result, agricultural productivity declined in several intensively cultivated territories.

Meanwhile, the northern districts, especially Muynak and Kungrad districts, experienced the most severe ecological and hydrogeological problems. In particular, groundwater frequently occurred at shallow depths of only 1.0–1.5 meters. Moreover, groundwater mineralization often exceeded 10–15 g/L due to strong evaporation, reduced river runoff, and the direct impact of the Aral Sea ecological crisis [3]. Consequently, intensive capillary rise transported large amounts of salts into surface soil layers [6, 953-956].

Furthermore, high concentrations of chlorides and sulfates caused strong salinization and degradation of soil structure. Humus content in Muynak and Kungrad districts decreased to critically low values ranging from 0.4% to 0.7%. In addition, microbial activity and

nutrient circulation became significantly weaker under saline conditions. Therefore, soil fertility sharply declined, while many agricultural lands became partially unsuitable for cultivation.

Another important result of the study was the identification of a strong correlation between groundwater mineralization and soil fertility indicators. Specifically, increasing groundwater salinity negatively affected humus accumulation, nutrient availability, water permeability, and biological activity. At the same time, shallow groundwater intensified waterlogging and secondary salinization processes [4].

Moreover, the study confirmed that the ecological consequences of the Aral Sea crisis played a decisive role in the deterioration of Muynak and Kungrad districts. Salt and dust transport from the exposed seabed further intensified soil contamination and environmental degradation. Consequently, desertification processes became more active in these northern territories.

Overall, comparative analysis revealed that deeper and less mineralized groundwater contributed to relatively stable soil conditions, whereas shallow and highly saline groundwater accelerated degradation processes. Therefore, sustainable groundwater regulation and effective reclamation measures remain essential for preserving agricultural productivity and environmental stability in the Republic of Karakalpakstan.

DISCUSSION

The results of this research clearly indicate that groundwater dynamics play a decisive role in shaping soil fertility across Karakalpakstan. In particular, the interaction between groundwater depth, mineralization, and irrigation practices determines the intensity of salinization processes and overall soil degradation. Therefore, the findings are consistent with previous studies conducted in arid and semi-arid regions of Central Asia.

First of all, the comparatively favorable conditions observed in Beruniy and Turtkul districts can be explained by deeper groundwater levels and relatively efficient drainage systems. As a result, salt accumulation in the upper soil layers remains limited. Moreover, these areas benefit from more stable irrigation regulation, which reduces the risk of secondary salinization. Consequently, soil fertility indicators remain higher compared to other regions.

In contrast, the situation in Nukus and Kegeyli districts demonstrates a transitional degradation pattern. Specifically, moderate groundwater mineralization combined with long-term irrigation without sufficient drainage has led to gradual salt accumulation. Furthermore, repeated irrigation cycles have intensified capillary rise processes. Therefore, soil structure and biological activity are slowly deteriorating in these central districts.

Meanwhile, the most critical ecological conditions were identified in Muynak and Kungrad districts. In particular, shallow groundwater combined with extremely high mineralization has created severe salinization stress. Additionally, the influence of the Aral Sea ecological crisis has significantly aggravated environmental conditions in these northern territories. Salt and dust deposition from the exposed seabed further accelerates soil degradation. Consequently, these areas represent the highest risk zones for agricultural loss.

Moreover, the results confirm a strong negative correlation between groundwater mineralization and key soil fertility indicators such as humus content, nutrient availability, and microbial activity. At the same time, shallow groundwater levels intensify waterlogging processes, which further reduce soil aeration and permeability. Therefore, both chemical and physical degradation processes act simultaneously, reinforcing each other.

Furthermore, the study highlights that anthropogenic factors, especially inefficient irrigation practices, play a central role in groundwater rise. In addition, climate aridity and high evaporation rates increase salt concentration in soil profiles. As a result, natural recovery processes are significantly weakened.

Importantly, these findings align with earlier scientific works by researchers of the Amu Darya delta region, who also emphasized the combined influence of hydrological imbalance and human activity on soil degradation. However, this study adds a clearer territorial comparison between southern, central, and northern districts, which allows for more precise ecological zoning.

Finally, it can be stated that sustainable soil management in Karakalpakstan requires integrated measures. On the one hand, improvement of drainage infrastructure is essential. On the other hand, optimization of irrigation practices and introduction of water-saving technologies are necessary. Therefore, without coordinated groundwater regulation, long-term soil fertility recovery will remain limited in the region.

CONCLUSION

This research study analyzed the influence of groundwater on soil fertility in the Republic of Karakalpakstan with a comparative focus on Beruniy and Turtkul (southern zone), Nukus and Kegeyli (central

zone), and Muynak and Kungrad (northern zone). Overall, the findings confirm that groundwater depth and mineralization are among the key factors controlling soil fertility in arid irrigated ecosystems. First of all, it was found that deeper groundwater with low mineralization in the southern districts contributes to relatively stable soil conditions, higher humus content, and better nutrient availability. Therefore, agricultural productivity in these areas remains comparatively sustainable. In contrast, moderate groundwater depth combined with increasing salinity in the central districts leads to gradual soil degradation. Moreover, insufficient drainage and continuous irrigation practices intensify salt accumulation, which negatively affects soil structure and biological activity. Meanwhile, the northern districts experience the most severe ecological stress. In particular, shallow and highly mineralized groundwater, together with the impact of the Aral Sea environmental crisis, accelerates secondary salinization and desertification processes. As a result, soil fertility in Muynak and Kungrad districts is critically low. Furthermore, the study confirms that groundwater salinity has a direct negative correlation with humus content, microbial activity, and nutrient availability. At the same time, shallow groundwater enhances capillary rise, which increases salt accumulation in upper soil layers. Therefore, it can be concluded that sustainable groundwater management is essential for preserving soil fertility in Karakalpakstan. In order to mitigate soil degradation, it is necessary to improve drainage systems, introduce water-saving irrigation technologies, and strengthen continuous monitoring of groundwater dynamics. Ultimately, only an integrated approach will ensure long-term ecological stability and agricultural sustainability in the region.

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