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ARTICLE

Impact of Soil Salinization and Groundwater Levels on Vegetation Cover in Irrigated Agroecosystems: An Analysis Based on GIS and Vegetation Indices

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Abstract

This study is devoted to analyzing the impact of soil salinization and groundwater levels on vegetation cover in irrigated agroecosystems using GIS technologies and vegetation indices. The research employed multispectral satellite imagery from Landsat 8–9 and Sentinel-2, data on soil salinity and groundwater levels, as well as the NDVI and SAVI vegetation indices. Spatial analysis was conducted in a GIS environment using IDW and Kriging interpolation methods, Moran's I spatial autocorrelation index, spatio-temporal regression, and time-lag techniques. The results showed that areas with high groundwater levels tend to exhibit increased soil salinity, which in turn leads to a deterioration of vegetation cover. It was also determined that changes in groundwater levels affect soil salinity and vegetation indicators with an average delay of approximately 3–4 months. Spatio-temporal monitoring based on GIS and vegetation indices serves as an important analytical tool for the scientific planning of land reclamation measures in irrigated agroecosystems, promoting the rational use of resources and ensuring the sustainability of agroecosystems.

Keywords: soil salinization, groundwater level, vegetation cover, GIS, vegetation indices, Syrdarya region.

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1 Introduction

Soil salinization is considered one of the most pressing ecological and agronomic problems globally, reducing the productivity of irrigated lands [9]. In irrigated agroecosystems, fluctuations in groundwater levels directly affect the reclamation status of soils as well as the development of vegetation cover. In particular, the proximity of groundwater to the soil surface intensifies the process of capillary rise, leading to the migration of dissolved salts into the upper soil horizons. As a result, the accumulation of salts in the root zone is observed, which leads to increased soil salinity and consequently reduces plant growth and crop productivity [10, 13].

The Syrdarya region is located in the central part of Uzbekistan and mainly consists of low-relief irrigated territories. In these areas, soil salinization and high groundwater levels are recognized as pressing issues in terms of ensuring ecological stability and increasing the efficiency of agricultural production [8, 11]. Studies confirm that the level and mineralization degree of groundwater directly affect the productivity of agricultural crops. Therefore, the need for rational use of water resources, the introduction of effective management mechanisms, and the scientific planning of reclamation measures is increasing [14].

Vegetation indices such as NDVI and SAVI are widely used as reliable indicators for assessing vegetation density and physiological condition [4, 12]. These indices allow the identification of vegetation dynamics, evaluation of plant stress conditions, and monitoring of the overall productivity of agroecosystems.

The integration of remote sensing data and GIS technologies enables a comprehensive analysis of the spatio-temporal relationships between soil salinity, groundwater levels, and vegetation cover [7]. Such an approach plays an important role in accurate modeling of ecological processes, identifying risk zones, and providing a scientific basis for territorial management decisions.

At the same time, the analysis of genotype-specific biological characteristics using digital methods contributes to increasing the efficiency of agronomic research. These approaches can be applied to determine plant tolerance to salinity, assess adaptation mechanisms, and predict productivity indicators [15].

While previous studies have largely relied on field observations and conventional statistical analysis methods, an integrated approach based on GIS and remote sensing technologies enables a deeper and more comprehensive investigation of the spatio-temporal relationships between soil salinity, groundwater levels, and vegetation cover [7]. This approach facilitates the identification of spatial differentiation of ecological processes, the assessment of their dynamics, and the improvement of forecasting accuracy.

The main objective of this study is to determine the impact of soil salinity and groundwater levels on the condition of vegetation cover in the irrigated agroecosystems of the Syrdarya region based on spatio-temporal analysis. The results of the study provide a methodological basis for developing practical recommendations aimed at scientifically grounded planning of reclamation measures, efficient water resource management, and ensuring the sustainability of agroecosystems.

2 Research Object and Study Area

The study was conducted in the irrigated agroecosystems of the Syrdarya region. This area is characterized by low relief, naturally high groundwater levels, a large share of irrigated lands, and the widespread occurrence of soil salinization processes [8, 11]. These factors significantly influence ecological balance and agricultural productivity in the region.

The degree of soil salinity, groundwater level, and the condition of vegetation cover were selected as the main research objects. Determining the relationships among these components is of significant scientific importance for assessing the reclamation status of regional agroecosystems and ensuring their sustainable development.

Soil data. Data on the degree of soil salinity and mechanical composition were compiled based on field observations and official statistical reports of the State Agroservice of the Syrdarya region [8]. These data were used to assess the reclamation status of the area and to determine the spatial differentiation of salinity levels.

Groundwater level. Data on the depth, mineralization degree, and seasonal fluctuations of groundwater in the region were collected, and the impact of groundwater levels on soil salinization processes was analyzed in a comprehensive manner [11]. These indicators were considered important factors in assessing the hydrogeological conditions of agroecosystems.

Remote sensing (RS) data. Multispectral images from the Landsat 8–9 and Sentinel-2 satellites were used in the study. Vegetation indices NDVI and SAVI were calculated to determine the density and physiological condition of vegetation cover [3, 4, 6, 12]. This approach enabled remote monitoring of vegetation dynamics and the detection of ecological changes.

3 Methodology

Spatial analysis. The spatial distribution of soil salinity and groundwater levels was mapped using a GIS software environment. To ensure spatial continuity and to predict missing point-based data, interpolation methods such as IDW (Inverse Distance Weighting) and Kriging were applied [2, 7].

4 Results and Discussion

Temporal analysis. Spatio-temporal analysis methods were applied to more comprehensively determine the relationships between groundwater levels and soil salinity. In particular, time-lag indicators and seasonal variations were evaluated, and the mechanisms of the influence of hydrogeological factors on vegetation processes were analyzed.

Vegetation index analysis. NDVI and SAVI vegetation indices were used to assess the density, condition, and stability of vegetation cover. The calculated indices were integrated into GIS maps and applied to identify the spatial manifestation of ecological processes associated with soil salinity and groundwater levels [1, 7]. This approach made it possible to determine the spatial differentiation of vegetation indicators and to evaluate the productivity level of agroecosystems.

Correlation and regression analysis. To determine the spatio-temporal relationships between soil salinity, groundwater levels, and vegetation cover, Moran's I spatial autocorrelation index, Pearson correlation analysis, and spatio-temporal regression models were applied. These statistical methods made it possible to identify the strength and direction of relationships among variables and to model ecological processes.

Data processing. All collected data were integrated into a unified geodatabase within a GIS environment and stored in shp and raster formats. Vegetation indices and soil salinity maps were compared over time, and the results were presented through statistical analysis and cartographic visualization methods. This process contributed to a more accurate assessment of the dynamics of ecological changes in the region.

Reliability of results. To ensure the accuracy and reliability of the research results, several verification measures were implemented: Landsat and Sentinel satellite images were synchronized; the coefficient of determination (R^2) was calculated to evaluate the accuracy of interpolation and regression models; and the resulting thematic maps were comparatively analyzed with field observation data [5, 10].

This methodological approach contributed to strengthening the scientific validity and practical applicability of the research results.

Spatial distribution of soil salinity. GIS-based analyses revealed significant spatial differentiation in soil salinity levels within the irrigated areas of the Syrdarya region. According to the thematic maps generated using IDW and Kriging interpolation methods, higher salinity levels were identified in low-relief areas. In these zones, the electrical conductivity (EC) of the soil solution reached values of 8–12 dS/m, indicating strong salinization. In contrast, areas with relatively higher relief showed EC values within the range of 2–4 dS/m, reflecting lower salinity levels [8, 10].

The obtained results confirm that low-relief conditions and the proximity of groundwater to the soil surface act as the main factors contributing to the formation of soil salinity. This indicates that hydrogeological conditions and relief characteristics have a significant impact on the reclamation status of agroecosystems.

Seasonal and spatial variation of groundwater levels. The conducted analyses showed that groundwater levels exhibit a pronounced seasonal dynamic. In particular, during the winter and spring months the average groundwater depth rises to 1.2–1.5 m, whereas in the summer season, due to intensified evaporation processes and changes in irrigation regimes, the groundwater level decreases to 0.8–1.0 m [11].

According to GIS maps and spatio-temporal analysis results, a statistically significant spatial relationship was identified between high groundwater levels and soil salinity (Moran's I = 0.67; $p < 0.01$). This indicator confirms that the spatial distribution of groundwater directly influences soil salinization processes and highlights the important role of hydrogeological factors in shaping the reclamation status of agroecosystems.

Vegetation cover and vegetation index results. Analyses based on NDVI and SAVI vegetation indices showed a significant decrease in vegetation density in low-relief areas with high levels of soil salinity. In these areas, NDVI values ranging from 0.2 to 0.4 indicate low vegetation activity and plant stress conditions.

Conversely, in areas where NDVI values exceed 0.6, soil salinity levels were relatively low (EC < 4 dS/m), and groundwater levels were located at moderate depths [1;7]. These results demonstrate that vegetation indices serve as reliable indicators for assessing vegetation cover conditions and are closely related to soil reclamation characteristics.

Spatio-temporal relationship analysis. Spatio-temporal regression and time-lag analysis revealed that changes in groundwater levels affect soil salinity and vegetation cover with a delay of approximately 3–4 months. This variation is associated with seasonal dynamics: in areas where groundwater levels are high during the winter season, salinity increases during the summer months, resulting in a reduction of vegetation cover [10, 13].

Spatial correlation and statistical results. The Pearson correlation between soil salinity and groundwater levels was r = 0.71 ($p < 0.01$); the inverse relationship between soil salinity and NDVI was r = 0.64 ($p < 0.01$); and the relationship between groundwater levels and NDVI with a time-lag effect was r = 0.59 ($p < 0.05$). The results indicate that soil salinity and groundwater levels significantly influence vegetation cover, and these processes can be quantitatively assessed using GIS and vegetation indices.

The results of this study demonstrate that soil salinity and groundwater levels significantly affect vegetation cover in the irrigated agroecosystems of the Syrdarya region. The spatio-temporal analysis conducted using GIS and vegetation indices (NDVI, SAVI) revealed that in areas characterized by low relief and high groundwater levels, soil salinity increases considerably, while vegetation cover decreases.

These findings are consistent with previous studies. Shahid and Khan (2021), in their investigation of primary salinization mechanisms at the global scale, confirmed that high groundwater levels and capillary rise intensify soil salinization [10]. Similarly, Sultonov (2018) identified the relationship between seasonal fluctuations of groundwater levels and soil salinity in irrigated areas of the Syrdarya region [11]. These results correspond closely with the GIS-based findings of the present study and clearly demonstrate the potential of spatial and temporal analysis for assessing ecological processes.

The results of the study indicate that changes in groundwater levels are associated with a time-lag effect on soil salinity and vegetation cover. This finding is important for understanding biological and ecological processes, as vegetation cover is sensitive not only to the level of soil salinity but also to the seasonal dynamics of groundwater. Analysis of NDVI and SAVI indices revealed a decrease in vegetation density in areas with high salinity, which is considered an important indicator for evaluating the effectiveness of biological restoration measures highlighted in the study by Kenzhaev et al. (2021) [10].

In addition, the integrated approach combining GIS and remote sensing (RS) demonstrated advantages over traditional field observations in identifying the complex spatio-temporal relationships among soil salinity, groundwater levels, and vegetation cover. Metternicht and Zinck (2003) emphasized that remote sensing technologies represent accurate and effective tools for monitoring soil salinity [7]. Similarly, Allbed and Kumar (2013) demonstrated the potential of RS for developing salinity maps and assessing vegetation responses, thereby supporting the planning of reclamation measures [1].

At the same time, the results revealed an existing scientific gap: spatio-temporal GIS-based monitoring in the irrigated areas of the Syrdarya region remains insufficiently developed, and precise indicators for optimizing reclamation measures are lacking. This study helps to fill this gap by providing a quantitative assessment of the impact of soil salinity and groundwater levels on vegetation cover.

The practical significance of the results lies in the fact that GIS- and RS-based monitoring enables effective planning of reclamation measures, efficient management of water resources, and maintenance of vegetation stability in the region. This approach contributes to improving the ecological sustainability of agroecosystems and enhancing their economic efficiency.

This study aimed to determine the complex spatio-temporal relationships among soil salinity, groundwater levels, and vegetation cover in the irrigated agroecosystems of the Syrdarya region using GIS and remote sensing (RS) technologies. The results demonstrated that in areas characterized by low relief and high groundwater levels, soil salinity increases significantly. This process negatively affects the density and stability of vegetation cover, leading to a decrease in vegetation index values (NDVI, SAVI).

Spatio-temporal analysis results showed that changes in groundwater levels affect soil salinity and vegetation cover with a delay of approximately 3–4 months, which can be explained by seasonal factors and hydrogeological processes. The results of Moran's I index and regression models quantitatively confirmed a strong positive relationship between groundwater levels and soil salinity, as well as a decrease in vegetation cover with increasing salinity levels.

Based on the obtained results, a spatio-temporal monitoring system relying on GIS and vegetation indices can serve as an effective scientific basis for monitoring the spread of salinity in irrigated areas, managing water resources, and planning reclamation measures. The findings of the study provide opportunities for developing practical recommendations aimed at ensuring agroecosystem stability in the region, improving soil health, and optimizing irrigation policies.

For future research, it would be advisable to develop more advanced modeling and monitoring systems that consider irrigation regimes, soil structure, and different types of salinization (saline, sodic, and alkaline).

5 Conclusion

The results of this study demonstrate that soil salinity and groundwater levels play a decisive role in shaping the condition and spatial distribution of vegetation cover in the irrigated agroecosystems of the Syrdarya region. GIS- and remote sensing–based analyses revealed significant spatial differentiation of soil salinity, particularly in low-relief areas where groundwater levels are located closer to the soil surface. In these zones, increased electrical conductivity values indicate strong salinization, which negatively affects vegetation density and physiological condition.

The spatio-temporal analysis confirmed a strong positive relationship between groundwater levels and soil salinity, while an inverse relationship was observed between salinity and vegetation indices. Time-lag analysis showed that changes in groundwater levels influence soil salinity and vegetation cover with a delay of approximately 3–4 months, reflecting the seasonal dynamics of hydrogeological processes and irrigation regimes. NDVI and SAVI indices proved to be reliable indicators for assessing vegetation condition and identifying stress zones associated with increased soil salinity.

The integration of GIS and remote sensing technologies demonstrated high effectiveness in identifying spatial patterns and temporal dynamics of soil salinization processes. This approach provides a reliable scientific basis for monitoring environmental changes, assessing the reclamation status of irrigated lands, and supporting evidence-based decision-making in agricultural management.

Overall, the findings highlight the importance of implementing GIS-based spatio-temporal monitoring systems for effective management of water resources and reclamation measures. Such systems can contribute to improving soil health, maintaining vegetation stability, and enhancing the ecological sustainability and productivity of irrigated agroecosystems in the Syrdarya region.

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