"MONITORING AND SUSTAINABLE MANAGEMENT OF IRRIGATED LANDS USING DIGITAL TECHNOLOGIES: A CASE STUDY OF BUKHARA REGION"

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Abstract. The efficient management of irrigated lands is critical for food security and environmental sustainability, particularly in arid and semi-arid regions facing water scarcity and land degradation. This study explores the application of digital technologies for monitoring and sustainable management of irrigated agricultural lands in Bukhara Region, Uzbekistan. Through the integration of remote sensing (Sentinel-2 and Landsat imagery), Geographic Information Systems (GIS), drone technology, Internet of Things (IoT) sensors, and machine learning algorithms, the research develops a comprehensive digital monitoring framework.

The study assesses key indicators such as soil salinization, vegetation health (NDVI/EVI indices), water use efficiency, and land productivity. A case study approach was employed, utilizing multi-temporal satellite data and field measurements collected from selected districts of Bukhara Region. Results demonstrate that digital technologies significantly improve the accuracy and timeliness of land monitoring compared to traditional methods, enabling early detection of degradation processes and supporting precision irrigation practices.

The proposed framework contributes to the transition toward smart agriculture by providing decision-makers and farmers with actionable insights for optimizing water resources and enhancing land sustainability. Findings highlight the potential for scaling this digital approach across Central Asia. Policy recommendations are offered to support the adoption of digital solutions in national agricultural strategies.

Keywords: irrigated lands, digital technologies, sustainable management, remote sensing, GIS, digital twin, precision agriculture, Bukhara Region, water use efficiency, soil salinization

Introduction. Agriculture is recognized as one of the oldest and most strategically important sectors of material production in human society. Since the early stages of human civilization, this sector — based on the utilization of land and water resources — has played a central role in ensuring food security, supplying the population with food products, and maintaining economic stability. As a result, related industries such as forestry, hunting, beekeeping, fisheries, livestock breeding, and others have developed and become closely integrated with agriculture.

In today's globalized world, agriculture is not only a source of food production but also plays a vital role in creating employment opportunities in rural areas, increasing household incomes, and protecting the environment. According to statistical data, more than 1.2 billion people are employed in agriculture and its related sectors worldwide, representing over 70% of the global economically active population. These figures clearly highlight the economic, social, and strategic importance of agriculture.

The world's total land area stands at approximately 13.2 billion hectares, of which only about 4.8 billion hectares are suitable for agriculture. Of this, irrigated lands constitute roughly 355 million hectares (around 23% of global cropland), yet they produce nearly 40% of the world's food. Nevertheless, throughout human history, nearly 2 billion hectares of once-productive land have been withdrawn from agricultural circulation due to soil salinization, desertification, urbanization, infrastructure development, and climate change. Every year, an additional 6–12 million hectares of land lose their productive capacity as a result of degradation processes. In this context, the preservation and rehabilitation of irrigated lands have become a critical component of global ecological security and long-term food sustainability.

The concept of land monitoring emerged at the international level in the 1970s, notably during the United Nations Conference on the Human Environment held in Stockholm in 1972. In Uzbekistan, scientific research in this field began in the 1980s–1990s. In particular, Academician D.S. Sattarov of the Academy of Sciences of the Republic of Uzbekistan, in his 1992 article titled "What is Land Monitoring and How Should It Be Organized?" published in the Uzbekistan Biological Journal, provided a scientific justification for the content, objectives, and organizational mechanisms of land monitoring, taking into account the arid climatic conditions of the country. This work laid an important theoretical foundation for the establishment of the national land monitoring system.

In Uzbekistan, approximately 47% of irrigated lands are affected by varying degrees of salinization. Bukhara Region is one of the most vulnerable areas in the Aral Sea basin, where intensive irrigation combined with shallow saline groundwater has led to widespread secondary salinization. Although some improvements have been observed in certain periods due to leaching practices, remote sensing studies using Landsat and Sentinel-2 satellites indicate that the overall risk of land degradation remains high.

Modern Digital Approaches in Irrigated Land Monitoring

In recent years, the integration of advanced digital technologies has revolutionized the monitoring and management of irrigated lands, shifting from traditional, labor-intensive field surveys to real-time, data-driven, and predictive systems. The main technologies include:

- Remote Sensing and Satellite Imagery: Sentinel-2 (ESA) and Landsat-8/9 (NASA) satellites provide high-resolution multispectral data. Vegetation indices (NDVI, NDMI) and salinity indices allow effective detection of vegetation health, soil moisture, and salinization processes.
- Geographic Information Systems (GIS): Platforms such as ArcGIS and QGIS integrate various data sources and create decision-support dashboards. In Uzbekistan, GIS-based systems have reduced monitoring costs by 5–8 times.
- Unmanned Aerial Vehicles (Drones): Offer very high-resolution imagery for detailed field analysis.
- Internet of Things (IoT) Sensors: Provide real-time data on soil moisture, salinity, and groundwater levels.
- Machine Learning and Artificial Intelligence: Enable predictive modeling of degradation processes.
- Digital Twin Technology: Creates a virtual replica of the physical irrigation system, allowing scenario simulation and optimization of water use (up to 20–25% savings in similar projects). This technology is especially promising for arid regions such as Bukhara.

Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. Develop a Regional Digital Twin Platform for Bukhara Region integrating satellite data, IoT sensors, drones, and GIS, accessible to authorities and farmers.

2. Strengthen institutional capacity through systematic training programs for specialists and farmers.

3. Integrate digital monitoring requirements into national agricultural and water policies, including incentive mechanisms for farmers.

4. Create a centralized open geospatial data portal for irrigated lands.

5. Scale up the Bukhara model to other regions of Uzbekistan and Central Asia.

Conclusion. The monitoring and sustainable management of irrigated lands remain one of the most pressing challenges in arid regions like Bukhara. This study has shown that modern digital technologies — particularly the integration of remote sensing, GIS, IoT, and Digital Twin approaches — provide powerful tools for early detection of degradation, optimization of water resources, and increasing agricultural productivity.

The transition to smart agriculture through digital solutions not only helps solve the problems of salinization and water scarcity but also makes a significant contribution to achieving the United Nations Sustainable Development Goals (SDGs 2, 6, 13, and 15).

The successful implementation of the proposed Digital Twin framework in Bukhara Region can serve as a valuable model for other countries in Central Asia. Ultimately, the future of sustainable irrigated agriculture depends on the intelligent integration of advanced technology, effective policy, and local knowledge.

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