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INTEGRATED HYDRO-GEO-MECHANICAL ASSESSMENT AND TECHNOLOGY FRAMEWORK FOR SHALLOW-DRAINAGE OPTIMIZATION IN LIMITED-WATER IRRIGATED AREAS

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Abstract
Efficient shallow drainage is crucial for sustaining agricultural productivity in limited-water irrigated areas, where water scarcity and soil degradation pose significant challenges. Conventional drainage designs often fail to account for the complex interactions among hydrological, geotechnical, and mechanical processes, leading to suboptimal performance. This study presents an integrated hydro-geo-mechanical assessment and technology framework for optimizing shallow drainage systems. The proposed approach combines field investigations, soil and water property analyses, and modeling of coupled hydro-mechanical processes to evaluate drainage efficiency and soil stability under water-limited conditions. Results demonstrate that the integrated framework improves water distribution, reduces waterlogging risks, and enhances irrigation efficiency compared to conventional methods. The findings provide both a scientific basis and practical guidelines for implementing optimized shallow drainage systems in water-scarce agricultural regions.

Keywords: Shallow drainage, hydro-geo-mechanical assessment, water-limited irrigation, soil-water interaction, drainage optimization, irrigation efficiency.

Introduction

Water scarcity is a pressing challenge in irrigated agriculture, particularly in arid and semi-arid regions where efficient water management is essential for sustaining crop productivity. In such contexts, shallow drainage systems are critical for controlling waterlogging, preventing soil salinization, and maintaining favorable soil conditions for crop growth. However, the effectiveness of conventional drainage designs is often limited because they typically focus on single aspects-either hydrological performance or soil stability-without considering the coupled interactions among water movement, soil properties, and mechanical behavior.

The integration of hydrological, geotechnical, and mechanical perspectives-referred to here as a hydro-geo-mechanical approach-offers a comprehensive framework for understanding and optimizing shallow drainage systems. Hydrological assessments provide insights into water distribution and flow dynamics, geotechnical analyses evaluate soil structure and permeability, and mechanical evaluations assess soil stability under varying moisture conditions. Despite its potential, this integrated approach has rarely been systematically applied to drainage optimization in water-limited irrigated areas.

Existing studies have primarily focused on either hydrological modeling or geotechnical design, often overlooking the interplay between soil-water interactions and mechanical responses that govern drainage efficiency. This knowledge gap can result in suboptimal designs that fail to maximize water use efficiency or prevent soil degradation.

The present study addresses this gap by developing an integrated hydro-geo-mechanical assessment and technology framework for shallow-drainage optimization in limited-water irrigated areas. The objectives of this study are to:

1. Analyze the coupled hydro-geo-mechanical behavior of soils under shallow drainage conditions.
2. Develop a technology framework for designing and implementing optimized shallow drainage systems.
3. Demonstrate the effectiveness of the framework in improving irrigation efficiency, reducing waterlogging, and enhancing soil stability in water-limited environments.

By providing both a scientific understanding and practical guidelines, this study aims to support sustainable water management practices and contribute to increased agricultural productivity in regions facing water scarcity.

Materials and Methods

Study Area

The study was conducted Nishan district of Kashkadarya region of the Republic of Uzbekistan, a semi-arid area characterized by limited water resources and intensive irrigation agriculture. The climate is continental, with annual precipitation ranging from 100–200 mm and high evapotranspiration rates, necessitating efficient water management. Soils in the study area are predominantly clay-loam to sandy-loam, exhibiting variable permeability and susceptibility to waterlogging under conventional irrigation practices. The fields are equipped with shallow drainage networks designed to maintain optimal soil moisture and prevent surface ponding.

Data Collection

Field investigations were carried out to collect data on soil, water, and drainage characteristics:

1. **Soil Properties:** Samples were taken from multiple depths (0–0.3 m, 0.3–0.6 m, 0.6–1.0 m) to determine texture, bulk density, porosity, hydraulic conductivity, and mechanical properties (shear strength, compressibility).

2. **Water Measurements:** Soil moisture content, groundwater levels, and drainage flow rates were monitored using piezometers, tensiometers, and flow meters.

3. **Topographic and Drainage Mapping:** High-resolution topographic surveys and GPS mapping of existing drainage networks were conducted to assess slope, drainage spacing, and network efficiency.

Experimental Design

A combination of field experiments and modeling was employed to assess the hydro-geo-mechanical interactions in shallow drainage systems:

- **Field Trials:** Controlled irrigation plots with adjustable shallow drainage outlets were established to observe water distribution, soil moisture dynamics, and soil settlement under different drainage configurations.
- **Laboratory Testing:** Soil samples underwent geotechnical testing, including consolidation, direct shear, and permeability tests, to quantify mechanical behavior and hydraulic properties.

Hydro-Geo-Mechanical Modeling

An integrated modeling framework was developed to simulate coupled hydrological and mechanical processes:

1. Hydrological Module: Soil-water flow was modeled using the Richards equation for unsaturated flow, calibrated with field-measured soil moisture and drainage discharge data.

2. Geotechnical Module: Soil mechanical response, including settlement and shear deformation under varying moisture conditions, was simulated using finite element analysis.

3. Integration Framework: Coupled simulations were performed to evaluate interactions between drainage efficiency, soil stability, and water distribution, enabling optimization of drainage design parameters such as spacing, depth, and outlet regulation.

Data Analysis

Model outputs were analyzed to determine:

- Drainage efficiency (% of excess water removed)
- Soil moisture distribution patterns
- Groundwater table fluctuations
- Soil settlement and stability indicators

Sensitivity analyses were performed to identify key parameters influencing shallow drainage performance, supporting the development of a practical technology framework for water-limited irrigated areas.

Results

Soil Properties and Hydrological Observations

Analysis of soil samples from the Kashkadarya region revealed that the soils are predominantly clay-loam in the upper layers (0–0.3 m) and sandy-loam at deeper depths (0.6–1.0 m). Bulk density ranged from 1.25 to 1.45 g/cm³, while porosity varied between 42% and 48%. Laboratory tests indicated that hydraulic conductivity increased with depth, from 0.8×10^{-5} m/s in the clay-loam topsoil to 2.5×10^{-5} m/s in sandy-loam subsoil. Mechanical testing showed that shear strength decreased with increasing moisture content, highlighting the importance of coupled hydro-mechanical analysis for drainage design (table 1).

Table 1. Soil Physical and Mechanical Properties in Nishan district of Kashkadarya Region

Depth (m)	Soil Type	Bulk Density (g/cm³)	Porosity (%)	Hydraulic Conductivity (m/s)	Shear Strength (kPa)
0–0.3	Clay-loam	1.25	48	0.8×10^{-5}	45
0.3–0.6	Clay-loam	1.32	46	1.2×10^{-5}	42
0.6–1.0	Sandy-loam	1.45	42	2.5×10^{-5}	38

Field monitoring of soil moisture and groundwater levels demonstrated that conventional shallow drainage systems were only partially effective in controlling waterlogging, with localized ponding observed in low-lying areas. Drainage flow rates ranged from 0.15 to 0.32 l/s per outlet, reflecting variability in soil permeability and slope conditions (table 2).

Table 2. Field Hydrological Observations under Conventional Shallow Drainage

Parameter	Observed Range	Notes
Soil moisture content (%)	28–42	Varies by depth and slope
Groundwater table depth (m)	0.5–1.2	Lower in highlands, higher in depressions
Drainage flow rate per outlet (l/s)	0.15–0.32	Dependent on soil permeability and slope

Hydro-Geo-Mechanical Modeling Outcomes

Simulations using the integrated hydro-geo-mechanical framework showed a strong correlation between drainage spacing, depth, and soil mechanical stability. Optimized shallow drainage configurations reduced waterlogging frequency by 35-50% compared to conventional layouts. Soil moisture distribution was more uniform, maintaining root-zone moisture within optimal ranges for crop growth.

The mechanical response of soils under varying drainage scenarios indicated that reducing drainage spacing and slightly increasing outlet depth minimized soil settlement and maintained shear strength above critical thresholds. Coupled analysis also highlighted areas where drainage modifications could prevent potential subsidence and structural degradation of drainage networks.

Table 3. Hydro-Geo-Mechanical Model Outcomes for Optimized Drainage Configurations

Drainage Parameter	Conventional System	Optimized System
Waterlogging frequency (events/season)	4.2	2.3
Average root-zone soil moisture (%)	38	34–36
Soil settlement (mm)	12	6
Drainage efficiency (%)	65	88

Sensitivity Analysis

Sensitivity analysis identified key parameters affecting drainage efficiency:

• **Soil hydraulic conductivity:** Higher conductivity significantly improved water removal but required careful consideration of slope and outlet design.

- **Drainage spacing:** Reduced spacing enhanced waterlogging mitigation but increased construction costs.
- **Soil mechanical properties:** Low shear strength zones required tailored drainage solutions to prevent instability.

Technology Framework Implications

The results support the feasibility of an integrated hydro-geo-mechanical framework for shallow-drainage optimization in water-limited irrigated areas. The framework enables the identification of optimal drainage configurations that balance water removal efficiency, soil stability, and cost-effectiveness, providing a practical tool for irrigation management in the Kashkadarya region.

Discussion

Hydro-Geo-Mechanical Interactions

The results of this study demonstrate the importance of considering coupled hydro-geo-mechanical processes for shallow-drainage optimization in water-limited irrigated areas. Soil properties, including hydraulic conductivity, porosity, and shear strength, were found to significantly influence drainage performance. The clay-loam topsoil, with lower permeability and higher water retention, was prone to localized waterlogging, whereas sandy-loam subsoil facilitated faster drainage but required careful assessment of mechanical stability. These findings are consistent with previous studies indicating that neglecting the interaction between soil-water dynamics and mechanical behavior can lead to suboptimal drainage designs and soil degradation.

Effectiveness of Optimized Drainage Configurations

The integrated modeling framework showed that adjusting drainage spacing and outlet depth improved both water removal efficiency and soil stability. Optimized configurations reduced waterlogging frequency by up to 45% and minimized soil settlement by 50% compared to conventional systems. This aligns with literature emphasizing that field-specific, adaptive drainage designs outperform uniform, conventional layouts in semi-arid regions. The observed improvement in root-zone moisture uniformity further supports enhanced crop water availability and potential yield increase.

Implications for Water-Limited Irrigated Areas

The Kashkadarya region, like many semi-arid regions, faces the dual challenge of limited water availability and soil degradation due to inefficient drainage. The hydro-geo-mechanical framework provides a practical approach for designing shallow drainage systems that account for both hydrological and geotechnical conditions. Sensitivity analysis revealed that soil hydraulic conductivity, drainage spacing, and soil mechanical properties are critical parameters to consider during planning. Implementing such integrated designs can improve water use efficiency, reduce waterlogging risks, and enhance long-term soil health, contributing to sustainable agricultural productivity in water-scarce environments.

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Comparison with Previous Studies

Previous studies on shallow drainage optimization often focused exclusively on hydrological modeling or geotechnical assessments. By integrating these approaches, our study bridges the gap and provides a comprehensive framework for field-specific optimization. The observed benefits of reduced waterlogging frequency, improved soil stability, and enhanced drainage efficiency demonstrate the superiority of this integrated approach over traditional designs, confirming recommendations from recent research emphasizing multi-disciplinary strategies for irrigation and drainage management.

Limitations and Future Research

While the integrated framework proved effective in the Kashkadarya region, its applicability to other regions with different soil types, climatic conditions, or irrigation practices may require calibration. Future research should include long-term monitoring of crop yield and soil health under optimized drainage configurations and explore coupling with advanced irrigation scheduling and water-saving technologies. Incorporating economic analysis would also help evaluate cost-benefit trade-offs for large-scale implementation.

Conclusion

This study demonstrates that an **integrated hydro-geo-mechanical framework** provides a robust approach for optimizing shallow drainage systems in water-limited irrigated areas, such as the Kashkadarya region. Key findings include:

1. **Coupled soil-water-mechanical interactions are critical**: Soil properties, including hydraulic conductivity, porosity, and shear strength, significantly affect drainage performance and stability.
2. **Optimized drainage configurations improve efficiency**: Adjusting drainage spacing and outlet depth reduced waterlogging frequency by up to 45%, minimized soil settlement by 50%, and enhanced root-zone moisture uniformity.
3. **Practical implications for irrigation management**: The framework offers a scientifically grounded and field-applicable tool for improving water use efficiency, preventing soil degradation, and supporting sustainable agricultural productivity in semi-arid regions.
4. **Key design parameters identified**: Sensitivity analysis highlighted soil hydraulic conductivity, drainage spacing, and soil mechanical properties as critical factors for drainage optimization.

The proposed framework can guide field-specific drainage design, ensuring both water and soil resource sustainability under limited-water irrigation conditions. Future work should extend its application to diverse regions, incorporate long-term crop yield monitoring, and evaluate economic feasibility for large-scale adoption.

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