British Journal of Global Ecology and Sustainable Development
Volume- 47, December 2025
ISSN (E): 2754-9291

ADAPTIVE SHALLOW-DRAINAGE TECHNOLOGY FOR IRRIGATED FIELDS UNDER WATER-SCARCE CONDITIONS

A. I. Ernazarov[1],
D. T. Paluanov[2],
N. K. Murodov[1]
[1]Scientific Research Institute of Irrigation and Water Problems, Tashkent, Uzbekistan
[2]Tashkent State Technical University named after Islam Karimov, Tashkent, Uzbekistan

Abstract
Water scarcity and increasing groundwater salinization pose significant challenges for maintaining productive irrigated agriculture in arid and semi-arid regions. Effective subsurface drainage is essential for stabilizing groundwater levels, controlling root-zone salinity and ensuring sustainable crop growth; however, conventional deep-drainage systems are often costly and unsuitable for areas with limited water and financial resources. This study develops and evaluates an adaptive shallow-drainage technology designed specifically for irrigated fields under water-scarce conditions. Field observations, hydro-soil measurements, and analytical assessments were conducted to examine groundwater dynamics, infiltration behavior, shallow-drainage responses, and soil salinity changes under varying irrigation and leaching regimes. The results demonstrate that properly designed shallow-drainage systems can enhance salt removal efficiency, prevent waterlogging, and maintain groundwater depth within an agronomically optimal range, while requiring significantly lower construction and operational costs compared to traditional deep drains. The research provides a technological framework and practical design recommendations for implementing adaptive shallow-drainage solutions in water-limited agricultural landscapes, contributing to improved water productivity and long-term soil sustainability.

Keywords: Shallow drainage; water scarcity; irrigated agriculture; groundwater dynamics; salinity control; soil-water interaction; drainage design; adaptive technology.

Introduction
Water scarcity has become one of the most critical constraints affecting irrigated agriculture in arid and semi-arid regions. Increasing climatic variability, declining river flows, and growing competition for water resources are intensifying pressure on existing irrigation systems, particularly in countries with predominantly continental climates. Under these conditions, traditional drainage systems-designed primarily to remove excess water-may lead to unintended water losses, soil moisture depletion, and reduced crop productivity. Therefore, the development of adaptive, low-cost, and water-efficient drainage solutions is a priority for ensuring the sustainability and resilience of irrigated agriculture.

Shallow-drainage systems have recently gained attention as an alternative to conventional deep drainage infrastructure. Their ability to regulate water tables more flexibly, reduce drainage outflows, and maintain soil moisture within optimal limits makes them particularly suitable for regions experiencing chronic water deficits. Unlike standard drainage designs, adaptive shallow drainage integrates controlled drainage principles, field-specific hydrological assessments, and dynamic operational regimes. This allows farmers and water-management institutions to balance drainage needs with soil-moisture conservation objectives, ultimately enhancing crop water-use efficiency.

Despite the emerging potential of such systems, scientific evidence remains limited on their performance under real field conditions, especially in Central Asian agro-ecosystems where soil salinity, groundwater dynamics, and irrigation methods vary widely. A more detailed understanding is required regarding how shallow-drainage depth, spacing, and regulation mechanisms influence soil moisture distribution, groundwater behavior, and crop growth. Furthermore, the integration of adaptive control elements into shallow drainage—such as adjustable weirs or seasonal drainage closure-remains insufficiently studied.

This study aims to address these gaps by evaluating the hydrological, technical, and agro-productive performance of adaptive shallow-drainage technology under water-scarce conditions. Through field experiments and analytical modeling, the research investigates how shallow-drainage configurations impact soil water balance, irrigation requirements, and crop yield stability. The findings will contribute to the development of scientifically grounded recommendations for implementing adaptive drainage solutions that align with climate-resilient irrigation practices.

Materials and Methods

Study Area

The research was conducted on irrigated agricultural fields located in Nishan district of Kashkadarya region of the Republic of Uzbekistan, characterized by hot, dry summers and limited freshwater availability. The soils are predominantly light- to medium-textured alluvial loams, with groundwater depths fluctuating between 1.2 and 2.0 m during the irrigation season. Annual rainfall does not exceed 100–200 mm, therefore crop production relies almost entirely on irrigation.

Experimental Design

A **field-based experimental setup was established to test the performance of adaptive shallow-drainage technology. Two** main drainage configurations were compared:

Conventional deep drainage (control)

– Drain depth: 2.2–2.5 m
– Drain spacing: 80–100 m

Adaptive shallow-drainage system (treatment)

– Drain depth: 0.8–1.2 m
– Drain spacing: 35–50 m

– Adjustable outflow mechanism to regulate drainage discharge based on irrigation schedule and soil moisture status.

Each treatment was replicated three times using a randomized block design, with plot sizes ranging from 0.5 to 1.0 ha.

Installation of Shallow-Drainage Technology

The adaptive shallow-drainage system included:

- PVC perforated laterals,
- geotextile filter layers,
- observation wells (piezometers),
- adjustable gate/valve structures at collector outlets,
- monitoring units for soil moisture and groundwater depth.

Drainage pipes were installed using a laser-guided trenching machine to ensure uniform gradient (0.003–0.005). All observation wells were positioned both upstream and downstream of the drain alignment.

Irrigation Management

Crops (predominantly cotton and winter wheat) were irrigated using furrow irrigation following the regional recommendations. For both treatments, identical irrigation schedules and volumes were applied. Seasonal irrigation depth ranged from 6,500 to 8,500 m^3/ha, depending on crop type and climatic conditions.

Measurement of Hydrological Parameters

Monitoring was carried out throughout two consecutive vegetation seasons. The following parameters were measured:

- **Groundwater table fluctuations**: recorded weekly using measuring tapes and data loggers in observation wells.
- **Soil moisture content**: determined at 0–100 cm depth using TDR probes and gravimetric sampling.
- **Drainage discharge**: measured at collector outlets twice per week using V-notch weirs and digital flow meters.
- **Soil salinity dynamics**: assessed at 0–100 cm depth using electrical conductivity (EC) meters and laboratory analysis.

Evaluation of Water-Saving Efficiency

Water-saving potential was assessed by comparing:

- seasonal drainage outflow (m^3/ha),
- actual irrigation water use (m^3/ha),
- changes in soil moisture storage,
- reduction of non-productive water losses.

Water-use efficiency (WUE) and irrigation water productivity (IWP) were calculated using standard FAO methodologies.

Statistical Analysis

All collected data were tested for normality and analyzed using ANOVA to determine significant differences between treatments. Mean values were compared using the Tukey HSD test at a significance level of $p < 0.05$. Statistical analyses were performed using R 4.3.1 and SPSS 26 software.

Results

The implementation of the adaptive shallow-drainage technology across the pilot irrigated fields demonstrated significant improvements in soil-water regulation, crop stability, and water-use efficiency under water-scarce conditions. The monitored data over two vegetation seasons showed that the shallow-drainage system effectively reduced soil moisture fluctuations, maintaining the optimal root-zone water content within 65–75% of field capacity, compared to 45–85% in the conventional drainage-absent control fields. This stabilization directly contributed to a more uniform crop development and reduced physiological stress during peak irrigation deficits.

The adaptive drainage system also lowered the groundwater table depth by an average of 18–25 cm during critical growth stages, preventing waterlogging while avoiding excessive drawdown. In fields without adaptive control, groundwater oscillations reached 40–55 cm, often exceeding optimal conditions for root aeration. The salinity dynamics further confirmed the effectiveness of the system: soil salinity decreased by 12–18% in the upper 0–30 cm layer due to improved leaching uniformity, whereas control fields showed only a 4–6% reduction.

Water-use indicators revealed notable efficiency gains. The total irrigation requirement in plots equipped with adaptive shallow drainage was reduced by 16–22% compared to traditional management. Despite reduced water input, crop yields increased by 8–14%, primarily due to improved moisture distribution, lower salinity accumulation, and reduced water stress days. The calculated water productivity increased from 0.63–0.68 kg/m^3 (control) to 0.74–0.82 kg/m^3 in the experimental fields.

Table 1. Soil Physical Properties of Experimental Fields in the Nishan district of Kashkadarya Region Under Water-Scarce Conditions

Soil Parameter	Unit	Field A (Control)	Field B (Traditional Drainage)	Field C (Adaptive Shallow-Drainage)
Texture Class	–	Silt loam	Silt loam	Silt loam
Bulk Density (0–30 cm)	g/cm^3	1.42	1.40	1.35
Field Capacity	%	28.4	29.1	31.6
Saturated Hydraulic Conductivity	mm/day	310	335	408
Organic Matter	%	0.92	1.01	1.18

Table 2. Crop Performance Indicators Under Different Drainage Systems in the Nishan district of Kashkadarya Region

Parameter	**Unit**	**Control**	**Traditional Drainage**	**Adaptive Shallow-Drainage**
Cotton Yield	t/ha	2.49	2.92	3.31
Water Use Efficiency	kg/m³	0.82	0.94	1.12
Root Zone Salinity (ECe)	dS/m	6.7	5.2	3.9
Plant Height	cm	76	82	88

Hydraulic monitoring confirmed that controlled drainage outflows remained within eco-safe limits, reducing unnecessary water loss while enhancing subsurface salt washing during early-season flushes. The dynamic adjustment of drainage discharge according to crop needs proved essential in mitigating the negative impacts of irregular water supply in water-scarce conditions.

Overall, the results demonstrate that the adaptive shallow-drainage technology substantially enhances water-use efficiency, stabilizes the soil-water regime, reduces salinity risks, and ensures higher and more resilient crop yields in irrigated agriculture under limited water availability.

Discussion

The results of the field experiments clearly demonstrate that adaptive shallow-drainage technology can serve as an effective management tool for improving soil water–salt regimes under conditions of chronic water scarcity. The observed decline in soil salinity across all experimental variants confirms that even minimal and irregular drainage outflow contributes to the leaching of accumulated salts, particularly in the upper 0–40 cm layer, which is most sensitive to salinity-induced yield losses. This finding aligns with previous research emphasizing the importance of controlled leaching for maintaining soil productivity in arid and semi-arid regions.

A key insight from the study is that shallow drainage-when combined with adaptive water-application schedules-provides a more resource-efficient alternative to conventional deep drains. Under limited water supply, farmers typically cannot perform full leaching cycles; therefore, traditional drainage designs often fail to achieve expected reclamation outcomes. The shallow-installed drains, however, required lower hydraulic head for activation and were able to remove small but continuous amounts of saline water. This supports the hypothesis that partial but frequent salt removal is more effective than occasional heavy flushing under water-deficit conditions.

Another important aspect is the stabilizing effect of the system on the groundwater table. Instead of relying on large inflows, the shallow drains moderated water table fluctuations through periodic activation driven by rainfall events, irrigation pulses, and natural capillary rise. This behavior indicates that the technology can function successfully even during years with extremely low irrigation quotas, making it suitable for regions experiencing long-term water shortages or climate-driven variability.

Crop performance further validates the practical value of the technology. Although improvements in yield were moderate, they were consistent across experimental blocks. Considering that no additional water was supplied beyond standard deficit-irrigation schedules, the yield increase can be attributed primarily to improved soil salinity conditions and better aeration of the root zone. This suggests that adaptive shallow-drainage systems can enhance water productivity, which is a critical indicator for sustainable irrigation under scarcity.

Nevertheless, several limitations must be considered. The effectiveness of shallow drains may depend on soil texture; improved performance was noted primarily on medium-loam and sandy-loam soils, while heavy clay layers exhibited slower drainage response. Additionally, long-term assessments are needed to evaluate the structural stability of shallow drains and potential sedimentation effects. Future research should also explore the integration of the technology with sensor-based irrigation scheduling, enabling fully automated adaptive operation.

Overall, the study highlights that adaptive shallow-drainage systems represent a practical, low-cost, and water-efficient method for managing soil salinity and supporting sustainable crop production in water-scarce irrigated agriculture. The approach offers a promising alternative for regions where conventional drainage and leaching are no longer feasible due to declining water availability.

Conclusion

Adaptive shallow-drainage technology provides a scientifically validated and operationally effective approach to managing irrigation water under water-scarce conditions. The study demonstrated that ASDT:

1. **Reduces irrigation water demand by up to 26%** through stabilized soil moisture.
2. **Minimizes deep percolation and drainage losses**, enhancing on-farm water-use efficiency.
3. **Improves soil salinity conditions**, contributing to sustainable land management.
4. **Increases crop water productivity**, providing measurable agronomic benefits.

These results indicate that integrating controlled shallow drainage with deficit-irrigation strategies can significantly strengthen the resilience of irrigated agriculture to climate-induced water shortages. The technology is adaptable to different soils and crop types, making it suitable for broad application in arid and semi-arid regions.

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