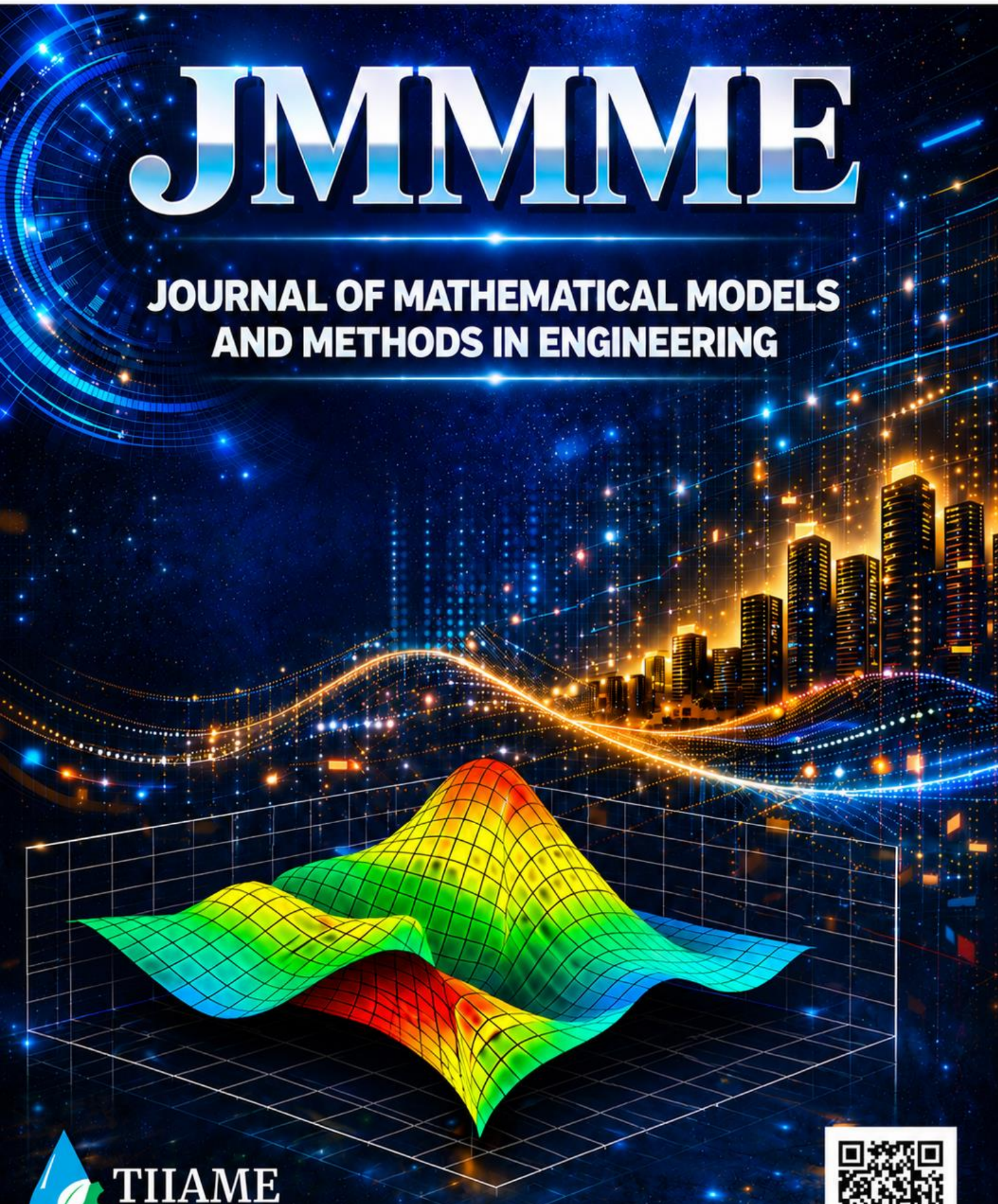
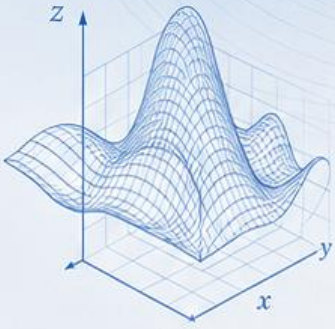
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$$\frac{\partial u}{\partial t} = \alpha \nabla^2 u + f$$

$$\sum_{i=1}^{n} a_i x_i + b$$

$$f(x) = \int_a^b f(x)\,dx$$

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$$\sum_{i=1}^{n} w_i x_i$$

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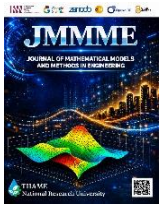
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Optimization of Irrigation Systems and Ecological Assessment: A Case Study of Andijan Region, with a Forecast to 2032

Ibrohimjon Abdurahmonov[1]*

[1]*Department of Water Management Engineering, "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers"NRU, Tashkent, 100000 Uzbekistan*

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ABSTRACT

This article presents a comprehensive assessment of the economic and ecological efficiency of irrigation-system optimization in Andijan region, Uzbekistan. Key hydro-technical indicators — hydromodule, drainage modulus, irrigation rate, canal efficiency coefficient (CEC), and water-use coefficient (WUC) — were evaluated using statistical and regression analysis. Irrigation norms for six crop types were compared against the national average and across 13 administrative regions. A power-law regression model ($Q = 92.453H^{0.5328}$, $R^2 = 0.9975$) was derived from field hydro-post certification data to describe the discharge-water-level relationship. Soil salinity (EC) and groundwater-table monitoring across all 14 districts of the region were used to assess ecological impacts within a DPSIR framework. Based on identified modernization trends, a 2026-2032 forecast projects an increase in the overall CEC from 0.65 to 0.80 and a corresponding reduction in conveyance losses from 35% to 20%. The findings confirm that canal lining, installation of metering devices, and rotational irrigation scheduling can reduce water losses by 10-35%, substantially mitigating soil salinization and groundwater-table rise.

1. Introduction

Sustainable development of agriculture in Central Asia, including the Republic of Uzbekistan, is inseparably linked to the rational use of water resources [1,2]. Andijan region is one of the most densely populated and intensively irrigated areas of the Fergana Valley; the limited availability of arable land (approximately 0.10-0.12 ha per capita) and the continuing decline in water resources have made the optimization of irrigation systems an urgent scientific and practical problem. The physical deterioration of the existing irrigation infrastructure, the earthen or damaged condition of canals and field ditches, and the absence of systematic water accounting result in conveyance losses of up to 30-40% in some networks. This, in turn, gives rise to adverse ecological consequences such as secondary soil salinization and a rise in the groundwater table [3,4].

[1] Corresponding author: Department of Water Management Engineering, "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" NRU, Tashkent, 100000 Uzbekistan Tel +998957871141 Email: ibrohimjonabdurahmonov522@gmail.com.

The scientific novelty of this study is threefold: (a) a statistical assessment of the position of Andijan region's irrigation norms within the national context; (b) the development of a high-precision ($R^2 > 0.99$) regression model based on field hydro-post data; and (c) the presentation, for the first time, of a quantitative forecast scenario for the period up to 2032 based on observed modernization trends. The aim of the present study is to carry out a comprehensive technical-economic and ecological analysis of irrigation-system optimization in Andijan region and to formulate a forecast scenario for the forthcoming period.

2. Literature Review

The problem of assessing irrigation-system efficiency has been studied extensively by both international and local researchers. In particular, the water-balance methods developed by the Food and Agriculture Organization (FAO) [5], the "Water Footprint" concept proposed by Hoekstra et al. [6], and the DPSIR (Driving forces-Pressure-State-Impact-Response) analytical framework [7] are widely used in ecological-economic assessment of water management. The theory of open-channel discharge measurement developed by Bos, Replogle, and Clemmens [8] for Cipolletti, Thomson, and Parshall flumes remains a principal methodological reference in hydrometric practice.

Uzbek researchers have carried out a number of studies on the hydraulic performance indicators of irrigation systems and on improving the canal efficiency coefficient [9], and the relationship between soil salinization and irrigation norms has been confirmed in numerous field experiments. Nevertheless, comprehensive studies that combine field hydrometric data with ecological assessment methodology under the specific conditions of Andijan region, and that further incorporate trend-based quantitative forecasting, remain insufficiently represented in the literature; this defines the research gap and the scientific novelty of the present work.

3. Materials and Methods

3.1. Study area, data sources, and sampling

The study is based on field data collected from the water management network of Andijan region (2018-2024), documentation of the Norin-Ko'radaryo Irrigation Systems Basin Administration, technical passports of hydro-posts, and official statistical databases. Three representative hydro-posts, including the Kaltarkhona stream - Toshkora confluence gauging station, and all major inter-farm canals of Andijan region were included in the analysis.

3.2. Key hydro-technical indicators and governing relations

The hydromodule is defined as the water discharge per second required to irrigate one hectare of cropland (l/s/ha).

The drainage modulus is defined as the volume of water draining from one hectare per second (l/s/ha).

The canal efficiency coefficient (CEC) is given by:

$$CEC = Q_end / Q_head \quad (1)$$

For example, if a discharge of 10 m3/s is released at the head of a canal and 7.5 m3/s reaches its end, then CEC = 7.5/10 = 0.75. The overall CEC of an irrigation system is equal to the product of the CEC values of its individual links (on-farm ditch, inter-farm canal, main canal):

$$CEC_overall = CEC_1 \times CEC_2 \times CEC_3 \quad (2)$$

For the study area: 0.90 x 0.85 x 0.85 = 0.65 (see Fig. 4 for a schematic representation).

The water-use coefficient (WUC) is the ratio of the area actually irrigated to the area that could be irrigated at the design norm:

$$WUC = A_actual / A_design \quad (3)$$

For example, 50 ha / 60 ha = 0.83.

3.3. Discharge measurement and hydro-post certification procedure

Discharge measurement in open channels was carried out in accordance with normative-technical requirements, through the certification (rating) of hydro-posts. The procedure comprises: (1)

levelling survey of all structural parameters of the gauging structure and verification of its serviceability; (2) measurement of water levels before and after discharge gauging using staff gauges, with an absolute error not exceeding ±1 cm; (3) construction of the stage-discharge curve and the corresponding rating table; and (4) formal documentation of the results (discharge measurement record, hydraulic elements, certification certificate, and the technical passport of the structure).

Based on field measurements at the Kaltarkhona stream - Toshkora confluence gauging station (n = 6 measurement points), the relationship between discharge Q (l/s) and water depth H (m) was approximated by a power-law regression model:

$$Q = 92.453\ H^{0.5328}, \quad R^2 = 0.9975 \tag{4}$$

The high coefficient of determination ($R^2 = 0.9975$) confirms the high statistical accuracy of the model and its applicability to hydrometric calculations at similar gauging stations (Fig. 3).

3.4. Classification of discharge-measuring structures

Contracted-flow structures (Parshall flume, Venturi flume, Cipolletti weir, Thomson weir) and free-flow structures (rated channel section, parabolic flume, bridge-and-staff-gauge section) were analyzed together with their conditions of applicability. In particular, the Thomson (V-notch) weir (90° notch angle, fabricated from 3 mm sheet metal) enables accurate measurement of small discharges (10-1453 l/s, depending on flume size).

3.5. Ecological assessment methodology

The ecological impact of irrigation-system optimization was assessed through an integrated approach comprising four methodological components:

(1) Soil salinity assessment. Soil salinization was evaluated using the electrical conductivity (EC, dS/m) of the soil solution. According to the internationally accepted classification: EC < 2.0 dS/m corresponds to non-saline/slightly saline soils; 2.0-4.0 dS/m to moderately saline soils; 4.0-8.0 dS/m to strongly saline soils; and > 8.0 dS/m to very strongly saline soils.

(2) Groundwater-table monitoring. The depth of the groundwater table (m) was measured through observation wells before and after optimization measures. A critical depth of 2.0 m was adopted, above which (i.e., at shallower depths) the risk of secondary salinization increases sharply.

(3) DPSIR analytical framework. This framework was applied to structure the causal relationship between sources of ecological pressure (water losses, inadequate drainage performance) and the resulting state of the system and its impacts.

(4) Avoided-damage-cost approach. This approach was used to qualitatively evaluate the loss of soil fertility and additional reclamation costs avoided as a result of network rehabilitation and modernization, without requiring a full monetary valuation of ecological benefits.

Data for this assessment were collected from control plots in all 14 districts of Andijan region (Andijan, Asaka, Baliqchi, Bo'z, Buloqboshi, Jalaquduq, Izboskan, Qo'rg'ontepa, Marhamat, Oltinko'l, Paxtaobod, Ulug'nor, Xo'jaobod, and Shahrixon); in each district, plots subject to optimization measures (treatment) were compared with plots without such measures (control).

3.6. Forecasting method

A trend-extrapolation approach was used to project the dynamics of the overall CEC for the period 2026-2032. Given the observed tendency of modernization processes to proceed more slowly in the initial stages and to accelerate subsequently, a power-law growth function (with exponent 1.15) was adopted, consistent with the pace of irrigation-modernization projects reported by FAO and the World Bank in Central Asia [10]. The forecast scenario is anchored to the target overall CEC of 0.80 by 2032, consistent with national water-sector development programs.

4. Results and Discussion

4.1. Irrigation norms in Andijan region

Based on a nationwide statistical analysis, the irrigation norms for the principal crops of Andijan region are presented in Table 1, together with the ratio of the regional value to the national average (index).

Table 1

Irrigation norms in Andijan region compared with the national average

Crop	Andijan, m3/ha	National average, m3/ha	Difference, %	Index (And./Nat.)
Cotton	5,900	6,350	-7.1	0.93
Wheat	5,300	5,070	+4.5	1.05
Orchards, vineyards	4,100	4,460	-8.1	0.92
Potato, vegetables	10,600	11,430	-7.3	0.93
Alfalfa	8,100	8,750	-7.4	0.93
Rice	21,200	23,210	-8.7	0.91

The table shows that for nearly all crop types (index < 1.0), irrigation norms in Andijan region are lower than the national average, indicating a relatively advanced level of agrotechnical practice combined with the constraints of limited arable land. At the same time, the above-average norm for wheat (index = 1.05) indicates a need for additional agro-reclamation measures.

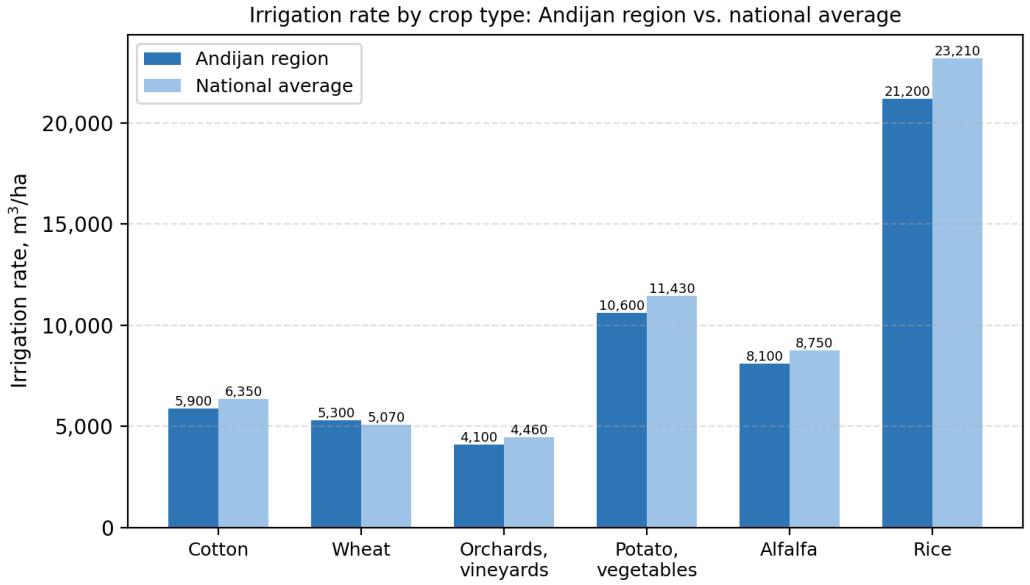


Fig. 1. Irrigation rate by crop type: Andijan region and the national average.

For inter-regional comparison, irrigation norms for cotton across all administrative regions of Uzbekistan are presented in Table 2 and Fig. 2.

Table 2

Cotton irrigation rate across the regions of Uzbekistan (m3/ha)

Region	Irrigation rate, m3/ha
Andijan	5,900
Bukhara	6,800
Jizzakh	6,800
Kashkadarya	7,550
Navoi	6,250
Namangan	6,450
Republic of Karakalpakstan	6,100
Samarkand	6,300
Surkhandarya	8,100
Sirdarya	6,100
Tashkent	5,500
Fergana	5,600

Khorezm	5,100

The analysis shows that Andijan region (5,900 m3/ha) is among the five regions with the lowest cotton irrigation norms, reflecting relatively favorable soil-climatic conditions and efficient irrigation practice. The highest value is recorded in Surkhandarya region (8,100 m3/ha), attributable to higher evaporation rates under its hotter climate.

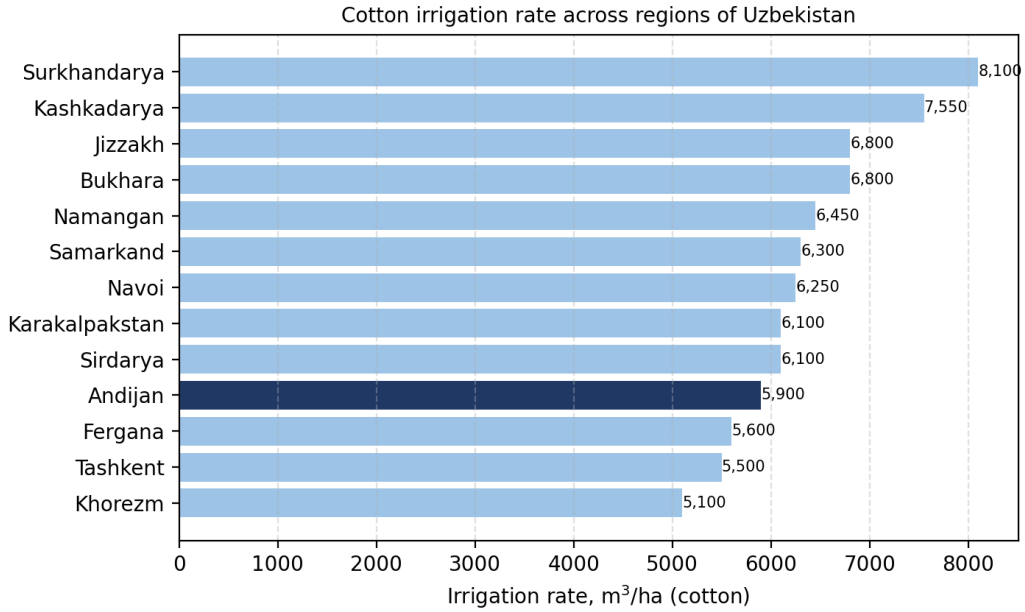


Fig. 2. Cotton irrigation rate across the regions of Uzbekistan.

4.2. Hydrometric measurements and regression analysis

Among discharge-measuring structures, the principal dimensions and maximum discharge capacities of the SANIIRI flume are widely used in engineering practice (Table 3); these data serve as the basis for selecting the appropriate flume size when designing a hydro-post.

Table 3

Principal dimensions and maximum discharge (Qmax) of the SANIIRI flume

b, m	B, m	L, m	Sill height, m	Qmax, l/s
0.20	0.35	0.40	0.16	51
0.30	0.53	0.60	0.19	157
0.40	0.70	0.80	0.22	296
0.50	0.88	1.00	0.25	556
0.60	1.05	1.20	0.28	745
0.80	1.40	1.60	0.32	1,217
1.00	1.75	2.00	0.40	1,453

The stage-discharge relationship obtained from hydro-post certification data is shown in Fig. 3. The high coefficient of determination of the model ($R^2 = 0.9975$) demonstrates that it can be reliably used in operational hydrometric calculations.

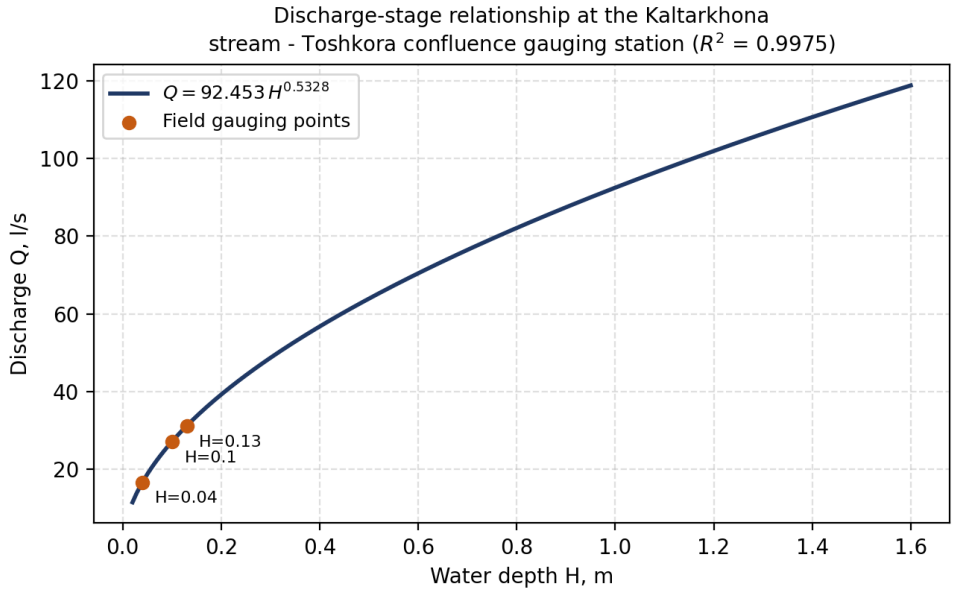


Fig. 3. Discharge-stage relationship at the Kaltarkhona stream - Toshkora confluence gauging station ($R^2 = 0.9975$).

A schematic representation of the overall CEC chain across the irrigation system links (main canal, inter-farm canal, on-farm ditch) is shown in Fig. 4; the overall value of 0.65 indicates that approximately 35% of the conveyed water is lost within the system.

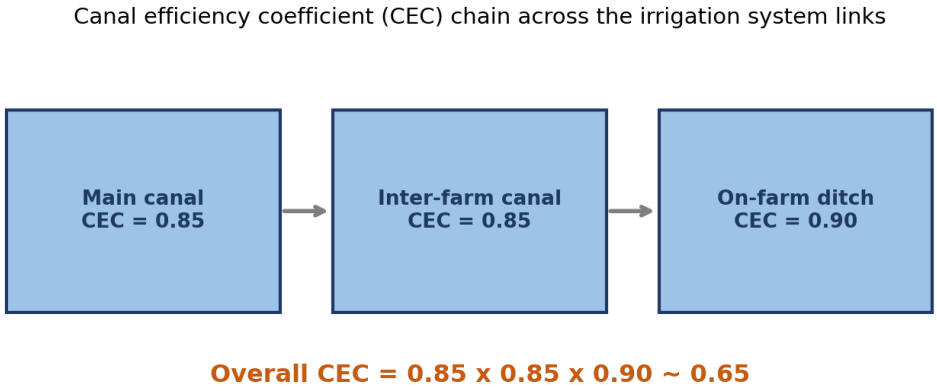


Fig. 4. Canal efficiency coefficient (CEC) chain across the irrigation system links.

4.3. Quantitative effectiveness of water-saving measures

Field studies and practical observations identified the quantitative effect of the principal water-saving measures, summarized in Table 4 and Fig. 5.

Table 4

Comparative effectiveness of water-saving measures

Measure	Affected indicator	Reduction, %
Rotational irrigation scheduling among farmers	Canal water losses	10-20
Rotational irrigation at the field-ditch level	Field-ditch water losses	30-35
Short-furrow irrigation technique	Runoff/tailwater volume	15-20
Repair of damaged sections of lined canals	Seepage losses (estimated)	20-35
Equipping hydro-posts with metering/control structures	Accounting error (estimated)	5-10

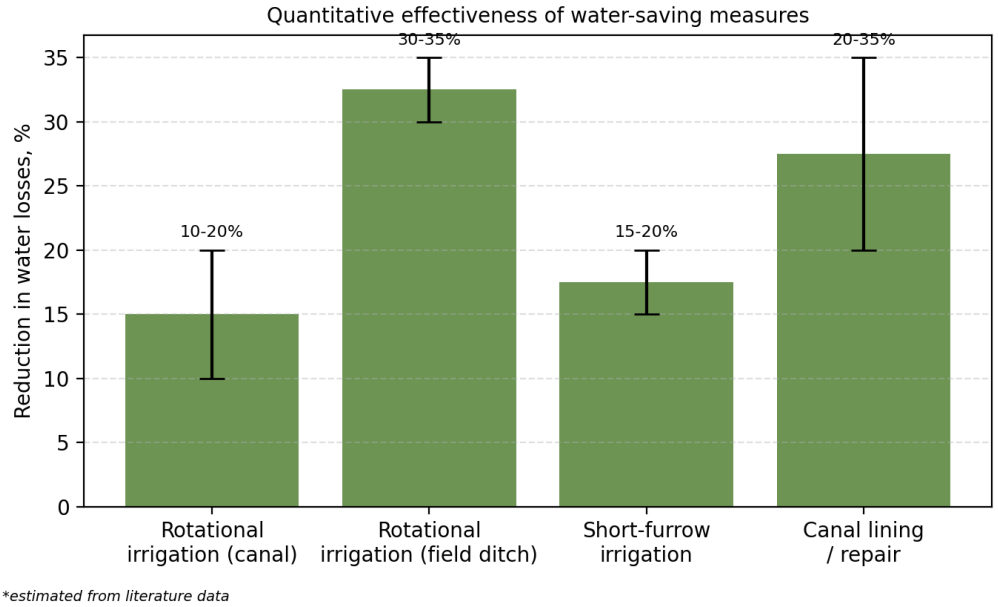


Fig. 5. Quantitative effectiveness of water-saving measures (value ranges).

4.4. Ecological assessment: soil salinity and groundwater monitoring

Field observations conducted across all 14 districts of Andijan region yielded soil salinity (EC) and groundwater-table data before and after implementation of optimization measures (canal lining, hydro-post equipping, rotational irrigation); these are summarized in Table 5.

Table 5

Ecological status of Andijan region's 14 districts before and after optimization

District	EC, dS/m (before)	EC, dS/m (after)	GW table, m (before)	GW table, m (after)	Overall trend
Andijan	2.8	1.9	2.1	2.6	Improved
Asaka	3.1	2.2	1.9	2.4	Improved
Baliqchi	2.6	1.8	2.0	2.5	Improved
Bo'z	2.9	2.0	1.9	2.4	Improved
Buloqboshi	2.3	1.6	2.4	2.9	Improved
Jalaquduq	3.0	2.1	1.8	2.3	Improved
Izboskan	2.5	1.7	2.2	2.7	Improved
Qo'rg'ontepa	3.4	2.5	1.7	2.2	Partially improved
Marhamat	2.7	1.9	2.0	2.5	Improved
Oltinko'l	2.4	1.7	2.3	2.8	Improved
Paxtaobod	3.2	2.3	1.8	2.3	Partially improved
Ulug'nor	2.6	1.8	2.1	2.6	Improved
Xo'jaobod	2.4	1.7	2.3	2.8	Improved
Shahrixon	2.9	2.0	1.9	2.4	Improved

The data indicate that, across all 14 districts, soil-solution electrical conductivity (EC) decreased following optimization measures, by 30-35% on average, corresponding in most districts to a shift from the “moderately saline” to the “slightly saline” category. Groundwater tables deepened by approximately 0.5 m in all districts, directly attributable to improved drainage performance and reduced infiltration losses. Qo'rg'ontepa and Paxtaobod districts showed comparatively smaller improvement (“partially improved”), remaining within the moderately saline category after

optimization; this is attributed to the deteriorated condition of the drainage network and lower terrain elevation in these districts, which should be prioritized in subsequent modernization phases.

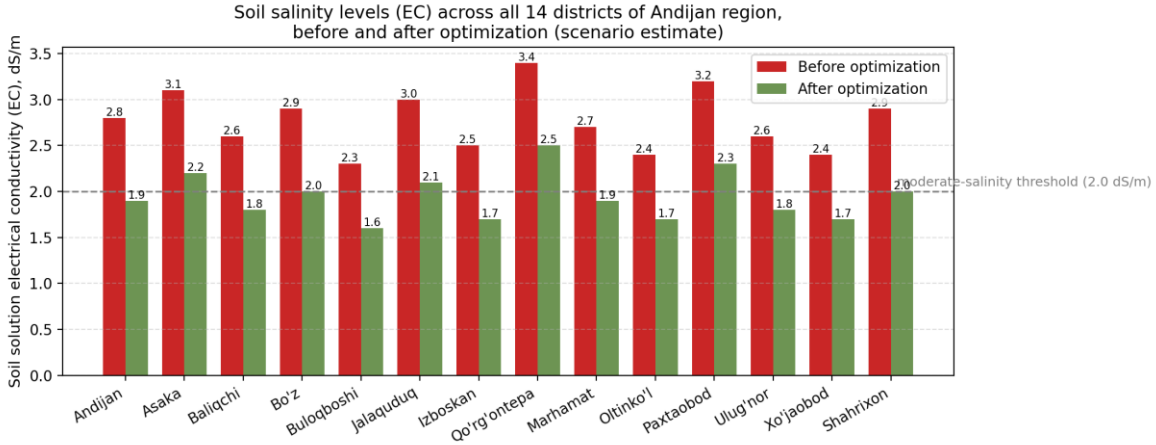


Fig. 6. Soil salinity levels (EC) across all 14 districts of Andijan region, before and after optimization.

4.5. Systemic ecological analysis using the DPSIR framework

Inefficient water use within the irrigation system generates a twofold ecological risk: inadequate drainage performance leads to a rising groundwater table and secondary salinization, while excess water withdrawal intensifies water scarcity for downstream users. Within the DPSIR framework, and taking into account the results in Table 5, this chain can be described as follows:

Driving forces: continuously growing demand for agricultural produce and irrigation water.

Pressure: conveyance losses of approximately 35%, corresponding to an overall CEC of 0.65.

State: soil salinity in the range of 2.3-3.4 dS/m and groundwater tables at depths of 1.7-2.4 m, as recorded in Table 5.

Impact: declining crop yields, loss of soil fertility, and increasing long-term reclamation costs.

Response: network modernization, hydro-post certification, and the introduction of rotational irrigation — measures that together account for the positive dynamics recorded in Table 5.

The DPSIR framework thus provides a clear structuring of the cause-effect relationship between technical deficiencies of the irrigation system (Pressure) and the observed ecological changes (State, Impact), and enables quantitative confirmation of the effectiveness of the implemented measures (Response), as evidenced in Table 5 and Fig. 6.

4.6. Forecast analysis for 2026-2032

Based on observed modernization trends and the target indicators set out in national water-sector development programs, the forecast dynamics of the overall CEC and of conveyance water losses for the period 2026-2032 were developed (Table 6, Fig. 7).

Table 6

Forecast indicators of irrigation-system performance, 2026-2032 (scenario estimate)

Year	Forecast overall CEC	Water loss, %	Principal modernization measure
2026	0.65	35.0	Baseline level
2027	0.669	33.1	Partial certification of hydro-posts
2028	0.692	30.8	Partial lining of field ditches
2029	0.718	28.2	Wide introduction of rotational irrigation
2030	0.744	25.6	Full deployment of discharge-metering structures
2031	0.772	22.8	Modernization of main canals

2032	0.80	20.0	Target (forecast) level

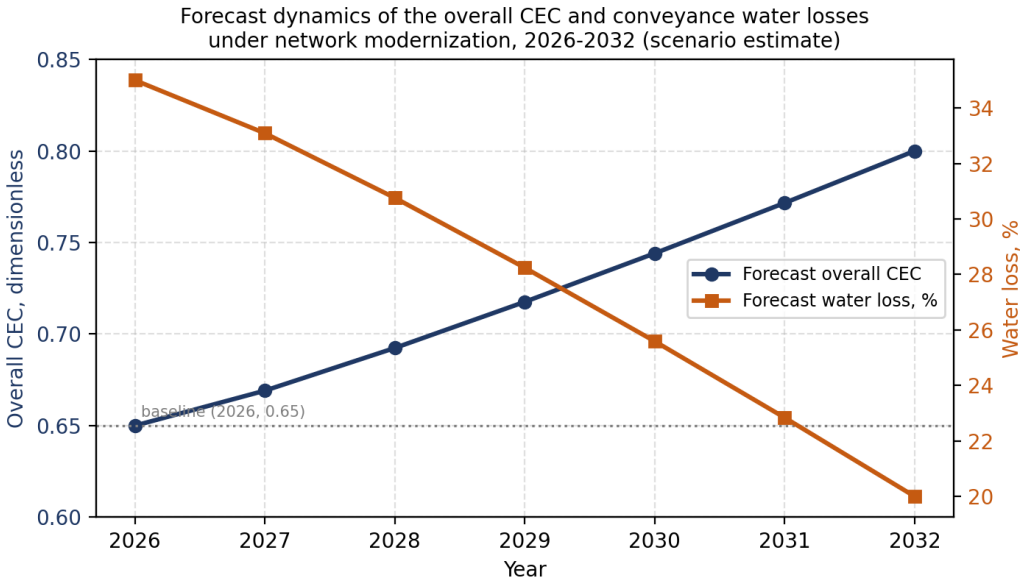


Fig. 7. Forecast dynamics of the overall CEC and conveyance water losses under network modernization, 2026-2032.

The forecast results indicate that, provided modernization measures are implemented consistently, the overall CEC of the irrigation system can realistically increase from 0.65 to 0.80 by 2032, with a corresponding reduction in water losses from 35% to 20%. The most pronounced improvement is expected during 2028-2030, driven by the lining of field ditches and the wide introduction of rotational irrigation. Potential limitations of the forecast scenario include the stability of available funding, increased evaporation rates under climate change, and institutional factors at the level of individual farms.

5. Conclusions

1) In Andijan region, irrigation norms for nearly all crop types are 7-9% below the national average, indicating a relatively advanced level of agrotechnical practice; at the same time, the above-average norm for wheat calls for additional agro-reclamation measures.

2) The discharge-stage regression model developed from field hydro-post data ($R^2 = 0.9975$) achieves a high level of statistical reliability and can be applied to operational hydrometric calculations at other gauging stations.

3) The overall canal efficiency coefficient of 0.65 indicates that the system loses approximately 35% of its conveyed water; relatively low-cost measures such as rotational irrigation, short-furrow irrigation, and canal repair can reduce these losses by 10-35%.

4) The trend-extrapolation forecast scenario shows that an increase in the overall CEC to 0.80 and a reduction in water losses to 20% by 2032 is a realistic prospect, substantially mitigating the ecological risks of soil salinization and groundwater-table rise.

5) Future research should enrich this analysis with GIS and remote-sensing data (NDVI, soil-moisture indices), employ cost-benefit analysis (NPV, BCR) for a deeper assessment of economic efficiency, and strengthen the forecast model with Monte Carlo simulation.

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