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AN INTEGRATED ORGANISATIONAL-ECONOMIC MODEL OF WATER LIMIT MECHANISMS IN TERRITORIAL WATER ALLOCATION: THE CASE OF ANDIJAN REGION DISTRICTS

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Abstract : *This paper presents an integrated organisational-economic model for territorial water allocation in the Andijan region (10 districts), encompassing water limit-setting, compliance monitoring, and graduated economic liability for over-limit use. The model formulates a linear programming problem that jointly optimises water limits by linking sectoral demand (agriculture, industry, utilities), resource constraints, and economic efficiency indicators. Empirical estimation using 2020-2023 panel data for Andijan region demonstrates that the integrated model significantly outperforms purely organisational (+27%) or purely economic (+24%) approaches, reducing aggregate water losses by 49.4% and improving water use efficiency by 53.4%.*

Keywords: *water limits, territorial allocation, integrated model, economic liability, optimisation, WUA, Andijan region, sectoral water allocation.*

INTRODUCTION

The scarcity of water resources and the absence of effective governance over them constitute one of the principal economic challenges facing developing states. In the Central Asian region, water losses in irrigation systems amount to 30–45% (FAO, 2021), a figure two to three times higher than international norms. In Uzbekistan, 87–92% of total water consumption falls to agriculture (Ministry of Water Resources of Uzbekistan, 2023), yet an effective limit system for regulating water allocation among regions and sectors has not yet been established.

The relevance of this issue is further intensified by climate change, population growth, increasing pressure on agricultural production, and the limited capacity of existing irrigation infrastructure. In water-scarce economies, inefficient allocation of water resources directly affects crop productivity, farmers' income, food security, and the financial stability of local agricultural systems. Therefore, the problem of water limits should not be viewed only as a technical or administrative issue, but also as an economic mechanism for balancing regional demand, sectoral priorities, and resource constraints.

Water limiting mechanisms have been studied within two main paradigms: (1) centralised administrative limiting, in which quotas are set by state bodies (Speed, 2009; Dukhovny & Sokolov, 2003); and (2) market-based allocation of water rights, which assumes optimal resource distribution through price signals (Grafton et al., 2011; Johansson et al., 2002). However, both approaches have certain limitations when applied separately. Administrative allocation often lacks flexibility and does not sufficiently reflect the actual economic efficiency of water use, while market-based mechanisms may be difficult to implement in regions where institutional capacity, metering systems, and water accounting practices remain underdeveloped.

In this context, the development of an integrated approach is of particular importance. Such an approach should combine administrative feasibility, economic rationality, territorial differentiation, and sectoral demand characteristics. For regions such as Andijan, where agricultural production is highly dependent on irrigation and water demand varies significantly across districts, the optimisation of water limits can become an effective tool for improving resource discipline, reducing losses, and strengthening accountability among water users.

However, these two approaches have not been modelled in integrated form at the territorial level — that is, for oblast-district systems. In particular, a formal mathematical model that simultaneously accounts for inter-sectoral demand variability, territorial preferences and constraints, and graduated economic liability levels is absent from the literature. This creates a methodological gap between the theoretical understanding of water allocation mechanisms and the practical needs of regional water management.

This research was conducted with the aim of developing an integrated model for optimising water limits using the example of 10 districts of Andijan region, evaluating it empirically, and providing practical recommendations. The proposed model is intended to improve the distribution of limited water resources by taking into account economic efficiency, territorial priorities, sectoral requirements, and responsibility for exceeding established limits.

The study addresses the following research question: by how much does an integrated limit model based on linear optimisation improve economic and organisational efficiency under conditions of territorial and sector-specific constraints? Answering this question is important not only for improving water governance in Andijan region, but also for developing a replicable methodological framework that can be adapted for other regions of Uzbekistan facing similar irrigation and resource allocation challenges.

LITERATURE REVIEW

The theory of water limiting rests primarily on two scholarly directions. The first is the water rights system developed within economic theory from Pigou's (1920) tax principle and Coase's (1960) theory of property rights (Grafton et al., 2011). The second is Ostrom's (1990) theory of common-pool resource management, which demonstrates the effectiveness of decentralised, community-based limiting mechanisms. Rogers et al. (2002) formalised the relationship between water pricing and limiting, showing within the IWRM (Integrated Water Resources Management) framework that limits are economically grounded and linked to price elasticity. Berbel & Exposito (2012) assessed the economic consequences of the water quota system in Spain, confirming the effectiveness of the quota market mechanism. Wang et al. (2019) found that a hierarchical limiting system under China's 'Three Red Lines' policy reduced volumetric losses by 23%.

The issue of territorial water allocation is treated as a distinct direction in the literature on regional economics and water resource management. Molle et al. (2010) compared 'power-based' and 'rule-based' approaches to water allocation, demonstrating higher institutional stability in the latter. Abdullaev & Mollinga (2010) studied water allocation at the WUA level in the Fergana Valley, analysing the combined effect of institutional and technical factors. For Central Asia, Dukhovny & Sokolov (2003) demonstrated the complexity of trans-territorial water allocation in the Aral Sea basin. Tashkentov & Tursunov (2021) evaluated irrigation reforms in Uzbekistan, clarifying that the ineffective operation of the quota mechanism at the territorial level is the principal problem. At the same time, the application of linear programming methods for water limit optimisation has not yet been empirically studied in Uzbekistan.

METHODOLOGY

The research employs a mixed methodology: (1) comparative analysis of international experience; (2) an optimisation model based on linear programming (LP); (3) empirical estimation using panel data for 10 districts of Andijan region for 2020-2023. Data sources: reports of the Ministry of Water Resources of Uzbekistan, the Andijan regional agricultural administration, the FAO

AQUASTAT database, World Bank and IWMI water management reports.

The integrated limit model was formulated on the basis of the following objective function and constraint system:

Objective Function:

$$\max Z = \sum_i \sum_j w_{ij} \cdot WUE_{ij}(L_{ij})$$

Where: i - district index ($i = 1, \dots, 10$); j - sector index ($j = 1, 2, 3$); L_{ij} - optimal limit for sector j in district i (mln m^3); w_{ij} - economic weight coefficient of the sector; WUE_{ij} - water use efficiency function.

Constraint System:

- (1) $\sum_i \sum_j L_{ij} \leq Q_{max} \cdot K_s$ [Overall source constraint]
- (2) $D_{ij,min} \leq L_{ij} \leq D_{ij,max}$ [Demand boundaries]
- (3) $\Delta L_{ij} = L_{ij,Actual} - L_{ij}^* \rightarrow P(\Delta L_{ij})$ [Penalty function]

K_s - climate correction coefficient (0.85-1.05); Q_{max} - annual maximum water source capacity; $P(\Delta L_{ij})$ - progressive penalty function (graduated system presented in Figure 3). The model was solved using LP-relaxation. Results were tested for robustness to random parameter variability through 1,000 Monte Carlo iterations. Statistical significance was assessed at the 95% level ($p < 0.05$).

THE INTEGRATED MODEL

The model consists of three functional blocks: (1) Input block - hydrological data, sectoral demand, economic parameters; (2) Optimisation core - LP objective function and constraint matrix; (3) Output block - optimal limits vector, monitoring signals, penalty calculations. The distinctive feature of the model is the presence of a feedback loop, which automatically compares actual consumption against optimal limits and activates the economic liability mechanism when deviations are detected.

Table 1.

Structure of the Integrated Water Limit Management Model

INPUT BLOCKS	OPTIMISATION CORE	OUTPUT BLOCKS
Territorial demand Sectoral demands Source constraints Economic parameters	Objective function Constraint matrix Limit calibration Scenario analysis	Optimal limits Monitoring signals Penalty calculations Feedback

FEEDBACK LOOP: Real-time monitoring → Over-limit detection → Automatic warning → Economic liability activation → Feedback Source: Model developed by the authors.

The optimal limit value for each district and sector is calculated using a five-stage algorithm. The algorithm combines LP solution and Bayesian updating, enabling the model to self-adapt as new data arrive.

Table 2.

Limit-Setting and Monitoring Algorithm

#	Stage	Details
1	Hydrological analysis	Determine precise water source capacity (Q_{max}); account for seasonal variability; determine climate correction coefficient (K_c)
2	Demand matrix construction	Determine minimum water requirement (D_{min}) and maximum demand (D_{max}) for each district/sector; set priority coefficients (w_i)
3	Objective function formulation	Calculate optimal limit vector $L^* = (L_1, \dots, L_n)$ based on $\max \sum w_i \cdot WUE_i(L_i)$; verify constraint conditions
4	Limit	Subject initial limit values to practical testing; assess statistical

	calibration	dispersion (σ); validate based on 95% confidence interval
5	Monitoring and adjustment	Compare monthly actual consumption with LiActual; send warning if $\Delta L >$ threshold; conduct quarterly recalibration

Source: Algorithm developed by the authors.

A five-tier progressive penalty system is proposed for cases of over-limit use. This system is based on the experience of Israel (Kislev, 2006) and Spain (Berbel & Exposito, 2012) and is adapted within the framework of Uzbekistan's water legislation (Water Code of the Republic of Uzbekistan, 2009).

Table 3.

Graduated Economic Liability Levels for Over-Limit Cases

Over-limit (%)	Level	Surcharge to Tariff (%)	Warning Type	Supervisory Authority Action	Deadline (days)
0-5%	I (permissible)	0 (automatic tariff)	Automatic SMS	-	-
5-15%	II (minor)	50	SMS + written warning	District WUA meeting	30
15-30%	III (moderate)	150	Official notice with report	Oblast water inspectorate	15
30-50%	IV (severe)	300	Fine + suspension order	Oblast governor	10
> 50%	V (critical)	500 + licence revocation	Court proceedings	Ministry of Water Resources	Immediate

Source: Developed by the authors on the basis of Kislev (2006), Berbel & Exposito (2012) and the Water Code of the Republic of Uzbekistan (2009).

EMPIRICAL RESULTS: ANDIJAN REGION

Analysis of data collected for the 10 districts of Andijan region over 2020-2023 showed that current limits are set on average 7.5% above optimal values (total 951.0 vs. optimal 879.9 mln m³). Over-limit cases totalled 38 instances across the four years, indicating potential for penalty collection of 2,336.9 mln soum (while the amount actually collected constituted 48%).

Table 4.

International Water Limiting Systems: Comparative Analysis

Country	Limiting System	Monitoring Mechanism	Economic Liability	Source
Australia	Water quota system (Water Act 2007)	Real-time SCADA monitoring	Progressive fines + suspension of water rights	Grafton et al., 2011
China	Three Red Lines policy (2011)	Provincial-district hierarchical monitoring	Budget withholding and official liability	Speed, 2009; Wang et al., 2019
Israel	Sector-specific annual limits	IoT sensors + central database	Triple tariff for excess consumption	Kislev, 2006; Tal, 2016
India (Gujarat)	WUA-level water shares	Canal operator weekly reports	Cancellation of payment system discounts	Meinzen-Dick & Bakker, 2001
Spain	Water Framework Directive	Basin management	Licence revocation +	Berbel & Exposito, 2012

	(2000/60/EC)	bodies	fines	
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Source: Compiled by the authors on the basis of Grafton et al. (2011), Speed (2009), Wang et al. (2019), Kislev (2006), Meinzen-Dick & Bakker (2001), Berbel & Exposito (2012).

Table 5.

Water Limit Optimisation Results by District, Andijan Region (2023)

District	Demand (mln m ³)	Current Limit (mln m ³)	Optimal Limit (mln m ³)	Difference (%)	Over-limit Cases (times)	Penalty (mln soum)
Andijan city	48.2	52.0	46.8	-10.0	3	128.4
Asaka	124.6	130.0	121.3	-6.7	5	312.7
Baliqchi	89.3	95.0	87.1	-8.3	4	198.5
Bo'ston	76.4	80.0	74.2	-7.2	2	87.3
Izboskan	112.8	118.0	109.6	-7.1	6	445.2
Jalolquduq	98.5	104.0	96.0	-7.7	3	201.6
Marhamat	87.6	92.0	85.3	-7.3	4	223.8
Oltinko'l	103.2	108.0	100.7	-6.8	5	378.9
Ulug'nor	94.7	100.0	92.4	-7.6	4	267.4
Xo'jaobod	68.3	72.0	66.5	-7.6	2	93.1
TOTAL	903.6	951.0	879.9	-7.5	38	2,336.9

Source: Ministry of Water Resources of Uzbekistan (2023) and authors' calculations.

Sectoral analysis shows that the agricultural sector has the greatest absolute savings potential (50.5 mln m³ or 7.4%), but the relative efficiency change (+12.3%) is lower than for the industrial sector (+18.7%). This situation indicates that capital costs in agriculture are high and that technological modernisation requires additional investment.

Table 6.

Limit Optimisation Results by Sector

Sector	Current Limit (mln m ³)	Optimal Limit (mln m ³)	Savings (mln m ³)	Savings (%)	WUE Change (%)
Agriculture	682.4	631.9	50.5	7.4	+12.3
Industry	142.8	128.5	14.3	10.0	+18.7
Utility Services	89.6	82.4	7.2	8.0	+9.4
Other sectors	36.2	37.1	-0.9	-2.5	-
TOTAL	951.0	879.9	71.1	7.5	+13.5

Source: Compiled from authors' calculations.

Four scenarios were compared: the traditional (baseline) situation, organisational reforms only, economic mechanisms only, and the integrated model. The results clearly demonstrated the superiority of the integrated model across all indicators. Integral efficiency (IE = 0.89) exceeded the sum of standalone organisational (IE = 0.72) and economic (IE = 0.71) approaches by 22.2% due to synergy effects.

Table 7.

Efficiency Comparison Across Four Scenarios

Indicator	Baseline	Organisational Only	Economic Only	Integrated Model
Water losses (%)	34.2	26.8	24.1	17.3

Over-limit cases (times/year)	38	22	18	7
WUE Index	0.58	0.71	0.74	0.89
Organisational Efficiency (OE)	0.54	0.78	0.61	0.85
Economic Efficiency (EcE)	0.60	0.64	0.80	0.87
Integral Efficiency (IE)	0.57	0.72	0.71	0.89
Synergy Effect ($\gamma \cdot OE \times EcE$)	-	-	-	0.20

Source: Compiled by the authors based on model simulation.

DISCUSSION

The research results lead to a number of important theoretical and practical conclusions. First, the integrated limit model combining organisational and economic components through linear programming demonstrated statistically significantly higher efficiency than standalone approaches (F-test: $p = 0.003$). This result empirically confirms Ostrom's (1990) principle of 'polycentrism' and the IWRM concept of Rogers et al. (2002) for territorial limit management. Second, inter-sectoral limiting revealed a certain trade-off: the growth in economic efficiency in the industrial sector is noticeably higher relative to agriculture. This corroborates the claim of Johansson et al. (2002) regarding the necessity of accounting for sector-specific elasticity differences in water pricing. However, in Uzbekistan's context, the need to protect agriculture for food security purposes raises the issue of balance in price and limit policy. The principal limitation of the research is that data are bounded by the period 2020-2023 and the long-term effects of climate change have not been incorporated into the model. Furthermore, political economy factors (lobbying, administrative pressure) may influence limit compliance, but these variables are not included in the model - an important direction for future research.

CONCLUSIONS AND RECOMMENDATIONS

This research presented and empirically evaluated an integrated organisational-economic model of water limiting mechanisms using the example of Andijan region for the first time on the basis of formal LP-optimisation. The principal scientific contributions are: (1) LP model structure combining territorial and sector-specific constraints; (2) incorporation of the synergy coefficient ($\gamma = 0.20$) into the integrated efficiency model; (3) a five-tier penalty scale adapted to Uzbekistan's legislation.

Practical recommendations:

1. Introduce an annual limit-setting system for the oblast water inspectorate based on the LP-optimisation module;
2. Integrate the real-time monitoring (SCADA/IoT) system with the WUA reporting system;
3. Formally incorporate the five-tier penalty system into water limit contracts and raise collection efficiency from 48% to 85%;
4. Recalibrate sector-specific weight coefficients (w_{ij}) every three years.

In future research, particular attention is recommended to: incorporating climate change scenarios into the LP model, applying stochastic programming methods, and integrating digital twin technology with the model.

In addition to the above, the following supplementary recommendations emerge from the research findings: (a) establish a permanent interdisciplinary working group comprising hydrologists, economists, legal experts, and IT specialists to oversee the implementation and continuous improvement of the proposed model; (b) develop a comprehensive training programme for water inspectorate staff, WUA managers, and farmers on the use of digital tools and interpretation of model outputs; (c) allocate dedicated budgetary resources for maintenance and upgrades of the SCADA/IoT infrastructure, with a target of replacing outdated sensors every five years; (d) create a regional water data hub that integrates information from meteorological stations, reservoir operators, groundwater

monitoring wells, and irrigation networks into a single accessible platform; (e) conduct annual public awareness campaigns on water conservation and limit compliance, leveraging mass media and community events to foster a culture of responsible water use; and (f) establish bilateral cooperation agreements with neighbouring regions to coordinate transboundary water management and share best practices in digital water governance.

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