OPTIMIZATION OF IRRIGATION REGIMES AND ECOLOGICAL ASSESSMENT OF RICE (ORYZA SATIVA L.) CULTIVATION BASED ON WATER CONSUMPTION MEASUREMENT: EVIDENCE FROM UZBEKISTAN, CENTRAL ASIA, CHINA AND INDONESIA

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Annotatsiya. *Ushbu maqolada O‘zbekistonda sholi (Oryza sativa L.) yetishtirishning sug‘orish rejimlarini optimallashtirish muammosi suv sarfini o‘lchash asosida ekologik baholash nuqtai nazaridan ko‘rib chiqiladi. Markaziy Osiyo davlatlari (Qozog‘iston, Tojikiston, Qirg‘iziston) va Xitoy Xalq Respublikasi tajribasi sug‘orish rejimi, tuproq mexanik tarkibi va sug‘orish me’yorlari bo‘yicha jadval va diagrammalar asosida qiyosiy tahlil qilingan. Indoneziyaning tomchilatib sug‘orish va navbatlab ho‘llash-quritish (AWD) texnologiyalari tajribasi sholi hosildorligi va barg maydoni indeksi (LAI) ga ta’siri nuqtai nazaridan baholangan. Yakuniy qismda FAO-56 Penman-Monteith uslubiyoti asosida GIS-modellashtirish yordamida mintaqalar kesimida evapotranspiratsiya (ETc) hisob-kitoblari va sxematik xarita taqdim etilgan. Maqola sholichilikda suv resurslaridan foydalanish samaradorligini oshirish va ekologik yukni kamaytirish bo‘yicha ilmiy asoslangan metodologik yondashuvni taklif etadi.*

Kalit so‘zlar: *sholi, sug‘orish rejimi, tomchilatib sug‘orish, AWD, tuproq mexanik tarkibi, sug‘orish me’yori, barg maydoni indeksi (LAI), evapotranspiratsiya, GIS, ekologik baholash.*

Аннотация. *В данной статье рассматривается проблема оптимизации режимов орошения при выращивании риса (Oryza sativa L.) в Узбекистане с позиции экологической оценки, основанной на измерении водопотребления. Проведён сравнительный анализ опыта стран Центральной Азии (Казахстан, Таджикистан, Кыргызстан) и Китайской Народной Республики по режиму орошения, механическому составу почвы и оросительным нормам с использованием таблиц и диаграмм. Оценено влияние капельного орошения и*

технологии переменного увлажнения и высыхания (AWD), применяемых в Индонезии, на урожайность риса и индекс листовой поверхности (LAI). В заключительной части на основе методики FAO-56 Пенмана-Монтейта представлены результаты ГИС-моделирования эвапотранспирации (ETc) по регионам и схематическая карта. Статья предлагает научно обоснованный методологический подход к повышению эффективности использования водных ресурсов и снижению экологической нагрузки в рисоводстве.

Ключевые слова: *рис, режим орошения, капельное орошение, AWD, механический состав почвы, оросительная норма, индекс листовой поверхности (LAI), эвапотранспирация, ГИС, экологическая оценка.*

Abstract. *This article examines the optimization of irrigation regimes for rice (Oryza sativa L.) cultivation in Uzbekistan from the standpoint of ecological assessment based on water consumption measurement. A comparative analysis of the experience of Central Asian countries (Kazakhstan, Tajikistan, Kyrgyzstan) and the People's Republic of China is presented with respect to irrigation regime, soil mechanical composition and irrigation norms, supported by tables and figures. The effect of drip irrigation and alternate wetting and drying (AWD), as applied in Indonesia, on rice yield and Leaf Area Index (LAI) is assessed. The final section presents GIS-based modeling of crop evapotranspiration (ETc) across production regions, together with a schematic map, following the FAO-56 Penman-Monteith methodology. The article proposes a scientifically grounded methodological framework for improving water use efficiency and reducing the ecological burden of rice production.*

Keywords: *rice, irrigation regime, drip irrigation, AWD, soil mechanical composition, irrigation norm, Leaf Area Index (LAI), evapotranspiration, GIS, ecological assessment.*

INTRODUCTION

Agriculture accounts for the overwhelming share of total water withdrawal in Central Asia, exceeding 80% regionally and reaching nearly 90% in Uzbekistan [1]. Uzbekistan has been identified among 33 countries expected to face water stress by 2040, notwithstanding its leading position within Central Asia in the deployment of water-saving technologies [2]. Rice (Oryza sativa L.) is among the most water-demanding field crops: under conventional continuous-flood management, field-level water requirements in Uzbekistan's rice-growing districts exceed 30,000 m3/ha

per season [4], a rate driven both by the region's arid continental climate and by traditional basin (check) irrigation practice.

Consequently, the optimization of irrigation systems for rice, informed by soil mechanical composition and validated through direct measurement of water consumption, constitutes both an agrotechnical and an ecological research priority. This priority is shared across the Syr Darya and Amu Darya river basins, whose waters are allocated among Uzbekistan, Kazakhstan, Tajikistan and Kyrgyzstan. The present article develops this problem along four complementary lines of evidence: (i) the comparative experience of Central Asian rice-growing countries; (ii) the regime, soil-texture and norm-setting practice of the People's Republic of China, the world's largest rice producer; (iii) the drip-irrigation and alternate wetting and drying (AWD) experience of Indonesia and its documented effect on yield and canopy development; and (iv) a GIS-based estimation of crop evapotranspiration that spatially differentiates irrigation requirements across Uzbekistan's rice-growing regions.

1. COMPARATIVE EXPERIENCE OF CENTRAL ASIAN COUNTRIES

1.1. Uzbekistan

Rice in Uzbekistan is concentrated in the Khorezm and Karakalpakstan regions and in the lower reaches of the Syr Darya basin. Field-level water requirements under conventional flood irrigation and basin (check) planting exceed 30,000 m3/ha per season according to FAO-based estimates for Khorezm [4]. Laser land-levelling reduces this requirement substantially: two-year field trials in Karakalpakstan recorded irrigation norms of 14,679 m3/ha and 14,506 m3/ha in successive seasons on laser-levelled fields — a reduction of 26-36% relative to the unlevelled control [5].

Soils of the Khorezm rice districts are dominated by silt loam, sandy loam and loam textures, which together constitute approximately 80% of all soil layers; organic-matter content is low, averaging 0.4-1.2% in the topsoil [6]. These properties indicate limited water-holding capacity, a factor that must be explicitly incorporated when irrigation norms are derived rather than transferred uncritically from other agro-ecological zones.

1.2. Kazakhstan

The Kyzylorda region is Kazakhstan's principal rice-producing area and depends on the Syr Darya. In the 2025 irrigation season, the Kyzylorda and Turkistan regions withdrew 3.5 and 3.4 billion m3 of water respectively, irrigating

125,000 and 400,000 ha [9]. Because of intensifying water scarcity, the sown area under rice in Kyzylorda is restricted to no more than 70,000 ha for 2026 in order to secure equitable allocation along the lower Syr Darya [9]. Field-scale research on the Bakbakti rice system in the Akdala irrigation massif (2022-2024, 311 ha) applied calibrated water gauges in canals, drains and paddy checks to quantify water and salt balances under alternative water-saving regimes [7]. In parallel, the Kazakh Rice Research Institute has released the early-maturing cultivar 'Syr Sulu' (105-110 days to maturity, versus 120-125 days for conventional cultivars), which is reported to require substantially less irrigation water while achieving yields of 80-85 centners/ha under proper agronomic management [10].

1.3. Tajikistan and Kyrgyzstan

In the headwater reaches of the Syr Darya basin, communities in Tajikistan and Kyrgyzstan divert river water for rice and other crops through local irrigation channels, with much of this flow failing to return to the main river system. This underscores the complexity of transboundary water management across the basin, which requires coordination among all four riparian states.

Taken together, the experience of these three countries indicates three converging directions for reducing water use in rice cultivation: (i) agrotechnical measures, including furrow, drip and AWD irrigation; (ii) breeding of early-maturing, low-water-demand cultivars; and (iii) institutional measures, including metering infrastructure and coordinated allocation, exemplified by the joint Kazakhstan-Uzbekistan agreement on installing water-metering devices on shared territory.

2. EXPERIENCE OF THE PEOPLE'S REPUBLIC OF CHINA: IRRIGATION REGIME, SOIL TEXTURE AND IRRIGATION NORMS

China is the world's largest rice producer. According to FAO regional water-withdrawal statistics, the national average agricultural water withdrawal for irrigated rice is approximately 7,500 m3/ha per year, markedly below the regional (Asian) gross average of 8,900 m3/ha [11]. This national figure, however, conceals substantial regional variation driven by climate, soil texture and the level of irrigation technology deployed.

Several water-efficient irrigation regimes are in operational use across China's rice-growing provinces. In Guangxi (southern China), a shallow-wet-drying (SWD) regime refills the paddy to its upper threshold only once soil moisture in the root zone falls to a lower threshold, reducing soil evaporation by an estimated 10-20% and improving the capture of rainfall [21]. In Shandong (eastern China), a

standardized field-water-control (SDC) regime is applied. In the arid Ningxia region of north-western China, rice has been cultivated under plastic-film-mulched drip irrigation; a three-year field trial recorded seasonal irrigation requirements of 3,128-3,946 m3/ha with water-use efficiency of 1.38-2.13 kg/m3 [20].

Soil mechanical composition is a determining factor in scheduling irrigation frequency and depth. Comparative field studies in arid north-western China found that loamy soils warranted fewer irrigation events (six per season) of larger depth (30-70 mm each), whereas sandy soils required more frequent irrigation (twelve events) of smaller depth (25-50 mm each) to maintain an equivalent root-zone water balance — a texture-dependent scheduling principle directly transferable to Uzbekistan's rice districts.

Table 1. Comparison of rice irrigation norms across regions of the People's Republic of China

Region / regime	Irrigation method	Irrigation norm, m3/ha	Water use efficiency, kg/m3
Guangxi (southern China)	Water-saving (SWD)	6,000-6,400	1.1-1.3
Shandong (eastern China)	Standardized field-water control (SDC)	5,600-6,000	1.0-1.2
Ningxia (north-western China)	Plastic-film-mulched drip irrigation	3,128-3,946	1.38-2.13
China, national average	Predominantly flood irrigation	~7,500	0.8-1.0

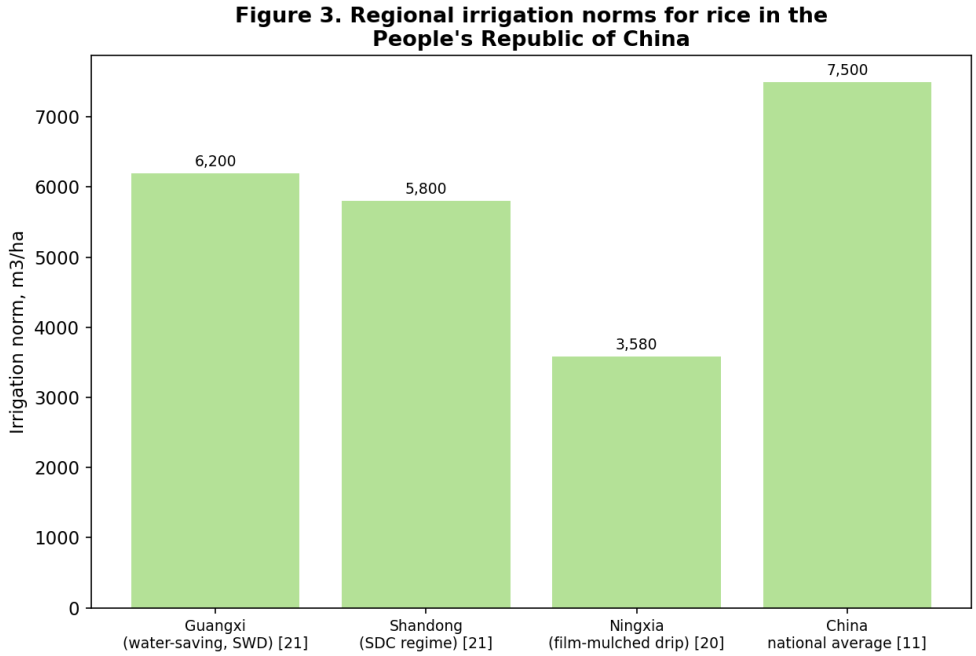

Figure 3. Regional irrigation norms for rice in the People's Republic of China

3. COMPARATIVE ANALYSIS OF UZBEKISTAN AND CHINA: IRRIGATION NORMS AND SOIL TEXTURE

The gap between Uzbek and Chinese irrigation norms for rice is attributable to two principal factors: climate (Uzbekistan's sharply continental, arid climate produces higher reference evapotranspiration than China's predominantly monsoon-influenced rice belt) and the level of irrigation technology (film-mulched drip irrigation and precision field-water control are considerably more widespread in China). Table 2 consolidates the principal indicators for the two countries.

Table 2. Summary comparison of rice cultivation indicators in Uzbekistan and China

Indicator	Uzbekistan (Khorezm / Karakalpakstan)	China (national / regional)
Predominant irrigation method	Continuous flood (basin/check)	Flood irrigation plus water-saving regimes (SWD, SDC)
Typical irrigation norm	30,000 m3/ha (conventional)	7,500 m3/ha (national average)
Norm under advanced technology	14,500-14,700 m3/ha (laser levelling)	3,100-6,400 m3/ha (regional)

Indicator	Uzbekistan (Khorezm / Karakalpakstan)	China (national / regional)
Soil mechanical composition	Silt loam / sandy loam, ~80% of profile	Region-dependent: loam and sandy soils
Soil organic matter	0.4-1.2%	Typically 1-2%, region-dependent
Principal ecological concern	Soil salinization; Aral Sea basin degradation	Groundwater depletion; CH4 emissions

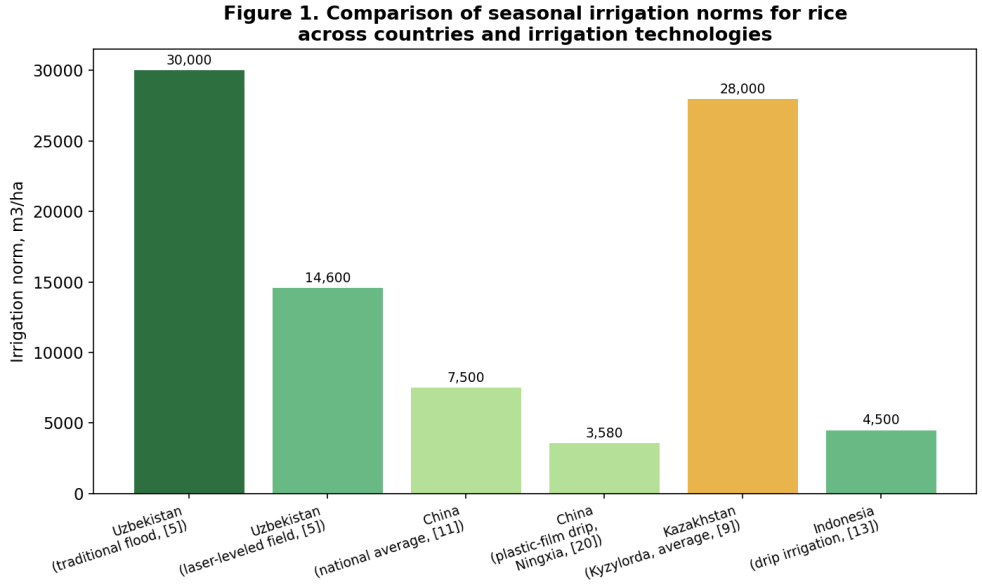

Figure 1. Comparison of seasonal irrigation norms for rice across countries and irrigation technologies

Table 3. Particle-size (mechanical) composition of paddy soils in the Khorezm region, by depth layer

Depth, cm	Sand, %	Silt, %	Clay, %	Organic matter, %
0-5	47	37	16	1.22
5-30	47	37	16	0.63
30-50	43	43	14	0.53
50-70	47	36	17	0.37
70-100	47	36	17	0.32

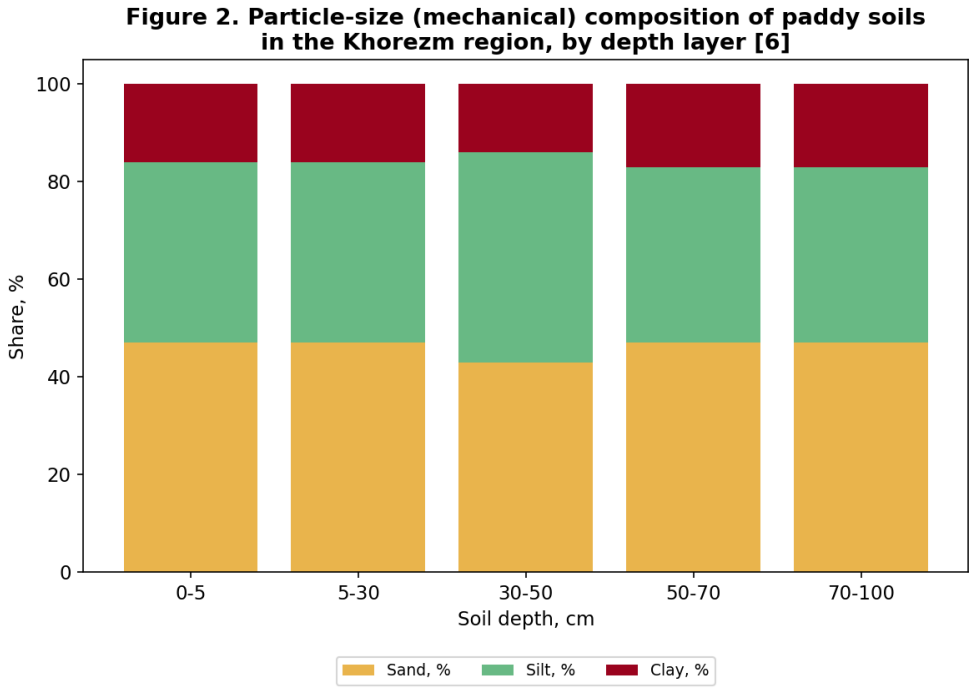

Figure 2. Particle-size (mechanical) composition of paddy soils in the Khorezm region, by depth layer [6]

4. EXPERIENCE OF INDONESIA: DRIP IRRIGATION AND ALTERNATE WETTING AND DRYING (AWD)

Indonesia has actively piloted drip irrigation, aerobic rice cultivation and AWD as alternatives to continuous flooding. Aggregated findings indicate that drip-irrigated rice can reduce water use by 30-50% relative to conventional flooding while increasing yield by up to 20%; the System of Rice Intensification (SRI) can increase yield by up to 50% while using 25-50% less water [12].

In a subsurface drip-irrigation trial with 0.8 m lateral spacing and a 1.0 L/h emitter discharge rate, grain yield rose significantly relative to the control (5,389 kg/ha versus 4,181 kg/ha); overall, drip irrigation improved yield in aerobic rice systems by 29% and reduced water use by 50%, doubling water productivity relative to the control method [13]. A dedicated study conducted in Central Java documented that AWD substantially reduced methane emissions without any accompanying yield penalty under local tropical conditions, although the authors note that evidence on the broader applicability of AWD across tropical agro-ecological zones remains limited [14].

This conclusion is reinforced by controlled experiments elsewhere: a two-year eddy-covariance study in the Lower Mississippi Delta found that AWD reduced seasonal methane emissions by 52% (2020) and 55% (2021) relative to continuous

flooding, without a significant yield penalty [15]. A global meta-analysis further estimates that AWD reduces methane emissions by 51.6% on average relative to continuous flooding [16].

Table 4. Methane (CH4) emissions under continuous flooding (CF) and AWD

Year	CF: CH4, kg/ha	AWD: CH4, kg/ha	Reduction, %	Effect on yield
2020	29	14	52	No significant difference
2021	75	34	55	No significant difference

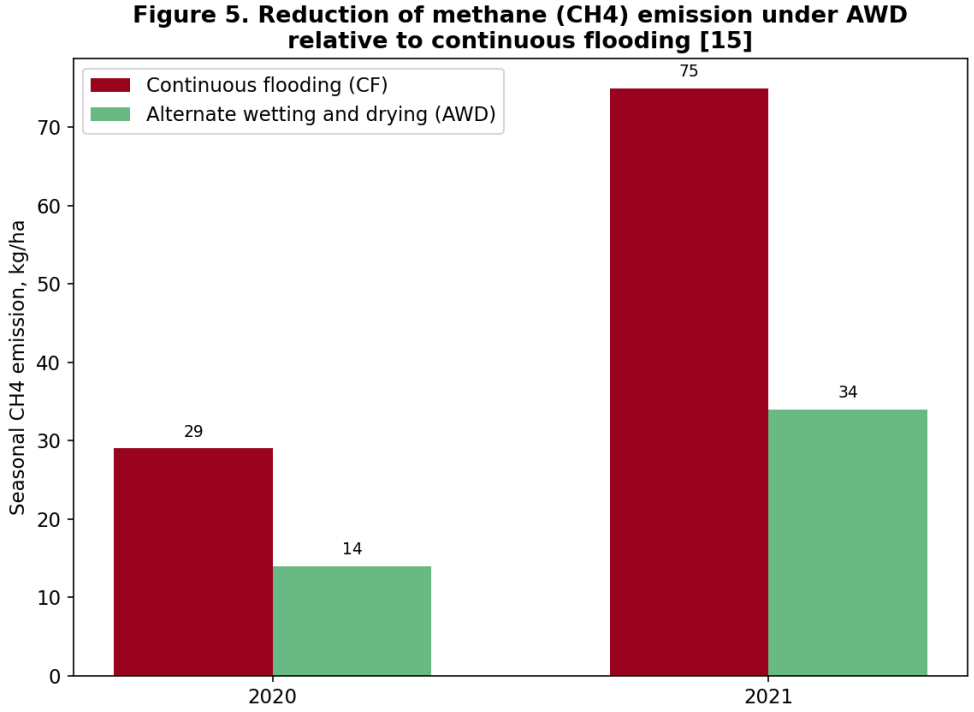

Figure 5. Reduction of methane (CH4) emission under AWD relative to continuous flooding [15]

5. EFFECT OF IRRIGATION REGIME ON LEAF AREA INDEX (LAI)

Leaf Area Index (LAI), defined as half the total green leaf area per unit ground area, is a principal structural indicator of canopy development and is widely used to monitor rice growth and forecast yield. High LAI at the booting and heading stages

is associated with more efficient interception of solar radiation, providing the physiological basis for subsequent grain-yield formation [17].

Irrigation regime directly modulates LAI dynamics. Under moderate and severe soil-water deficit, LAI declines significantly at the grain-filling and maturity stages, whereas mild water stress may leave LAI largely unaffected, as documented in a two-year field trial with super hybrid rice cultivars [18]. The LAI-yield relationship is, however, non-linear: excessive LAI, for instance under high planting density, can impair grain filling and depress yield, because an optimal LAI exists for each crop and cultivar - rice generally requiring a substantially higher optimal LAI than crops such as sorghum. Correspondingly, lower LAI reduces crop water demand, a relationship first formalised by Fukai (1988) [19].

Under drip irrigation and AWD, the combination of optimized water and nutrient (fertigation) management has been shown to produce higher LAI values than either factor alone, while furrow-irrigated rice cultivars have been reported to develop greater leaf area than those grown under continuous flooding. These findings support the inclusion of LAI monitoring, alongside yield and water-use measurements, as a core physiological indicator in future field experimentation in Uzbekistan.

Table 5. LAI values across rice growth stages under different irrigation regimes (synthesized from [17], [18])

Growth stage	Full irrigation (control)	Mild water deficit (AWD)	Severe water deficit
Transplanting	0.3	0.3	0.3
Tillering	1.8	1.7	1.4
Stem elongation	3.6	3.4	2.6
Heading	5.1	4.8	3.3
Grain filling	4.6	4.4	2.5
Maturity	2.4	2.3	1.1

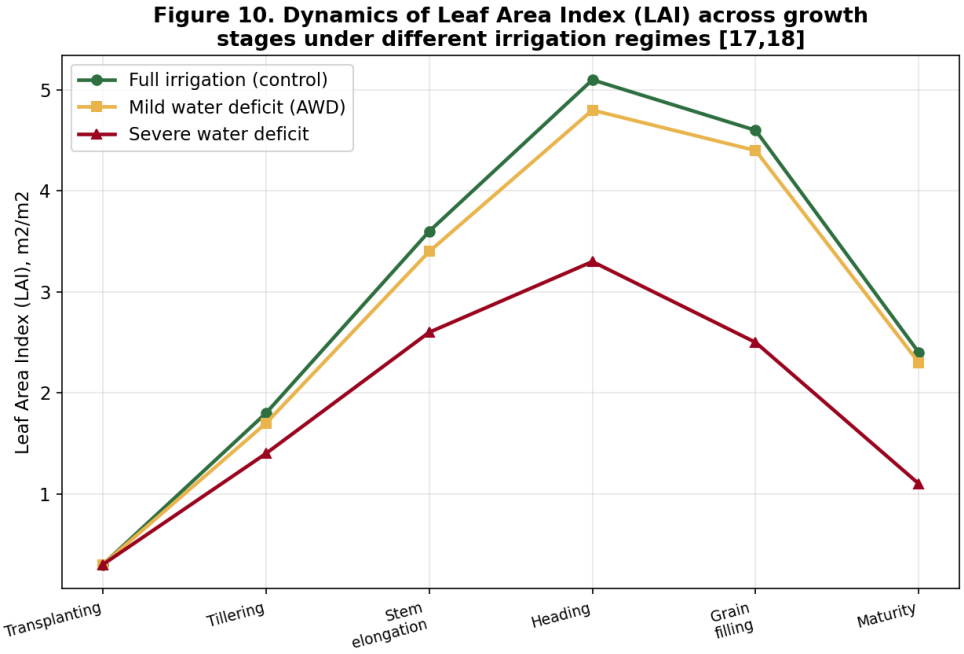

Figure 10. Dynamics of Leaf Area Index (LAI) across growth stages under different irrigation regimes [17,18]

6. YIELD, WATER USE AND WATER PRODUCTIVITY: A SYNTHESIS

Consolidating the evidence presented above, water productivity (WP, kg grain per m3 of water applied) provides the most policy-relevant metric for comparing irrigation regimes across the countries reviewed, since it jointly captures agronomic and ecological performance.

Table 6. Water productivity (WP) by irrigation regime

Irrigation regime	Water use, m3/ha	Yield, kg/ha	WP, kg/m3
Continuous flooding (control)	30,000	5,500	0.18
Furrow irrigation	15,600	6,260	0.40
Surface drip irrigation	14,500	5,850	0.40
Subsurface drip irrigation	14,000	6,540	0.47
AWD	22,000	5,900	0.27

Irrigation regime	Water use, m3/ha	Yield, kg/ha	WP, kg/m3
SRI	15,000	6,900	0.46

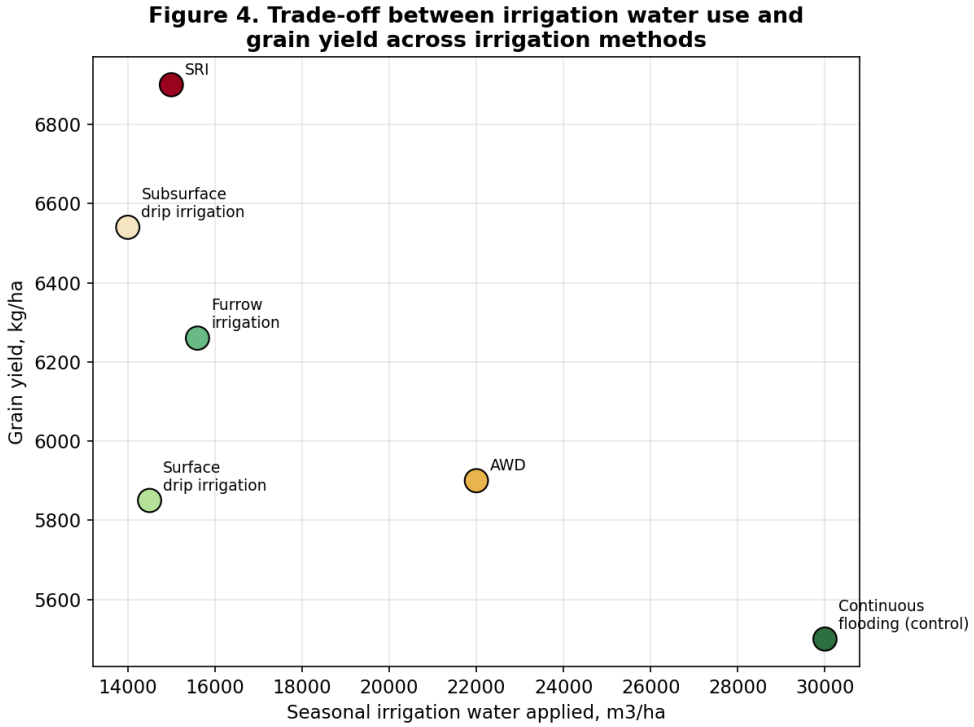

Figure 4. Trade-off between irrigation water use and grain yield across irrigation methods

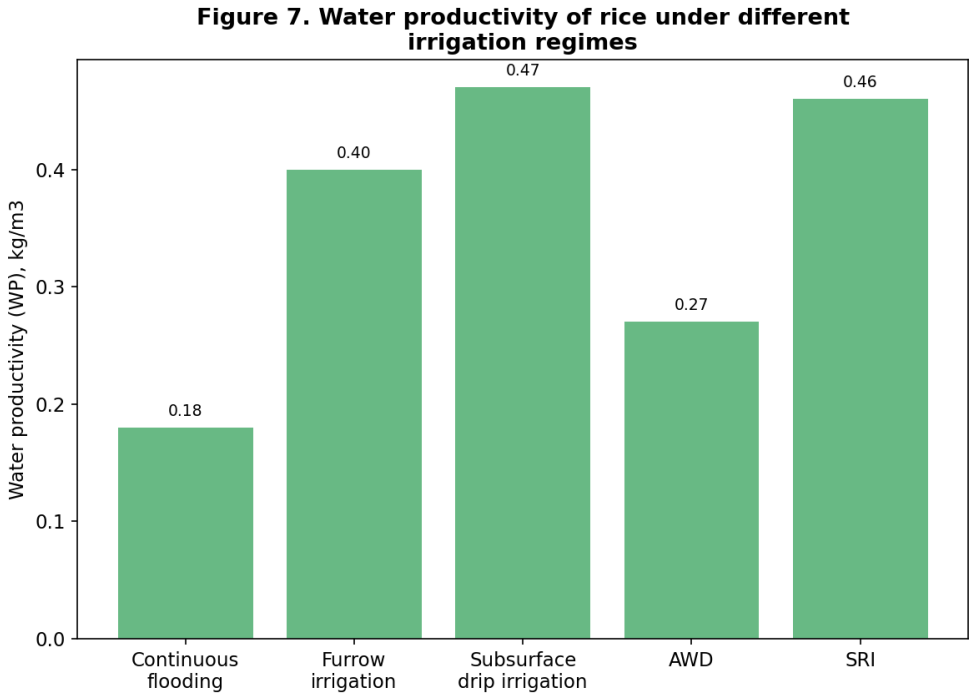

Figure 7. Water productivity of rice under different irrigation regimes

These data indicate that subsurface drip irrigation and SRI deliver the highest water productivity among the regimes reviewed, whereas AWD, despite a comparatively modest water-productivity advantage over continuous flooding, remains the most effective single regime for methane mitigation. Regime selection therefore involves an explicit trade-off between maximizing water productivity and minimizing greenhouse-gas emissions, which should be resolved according to site-specific ecological priorities rather than by water productivity alone.

7. GIS-BASED ESTIMATION AND MAPPING OF EVAPOTRANSPIRATION

A rigorous determination of rice water requirement requires estimation of crop evapotranspiration (ETc), computed as the product of reference evapotranspiration (ET0) and a crop coefficient (Kc): ETc = Kc x ET0. Reference evapotranspiration is conventionally estimated using the FAO-56 Penman-Monteith equation, which combines net radiation, air temperature, humidity and wind-speed data; where the full parameter set is unavailable, the Hargreaves-Samani equation is recommended as a data-parsimonious alternative [22]. Applying both methods to observations from thirteen meteorological stations across Uzbekistan, Masaliyeva et al. (2024) confirmed that the Hargreaves-Samani formula, once locally calibrated, provides estimates suitable for end-user irrigation scheduling under the data-scarce conditions typical of the region [8].

Rice exhibits a substantially higher seasonal ETc than most field crops: microlysimeter measurements report a seasonal mean water consumption of 6.7 mm/day, rising to 8.3 mm/day at the panicle-enlargement stage. In continuously flooded systems, ETc is only one component of total field water requirement; deep percolation and lateral seepage losses add substantially to the total, which explains why field-level irrigation requirements in Khorezm (>30,000 m3/ha, [4]) considerably exceed the crop's physiological water demand as such.

A GIS-based spatial disaggregation of ETc across Uzbekistan's principal rice-growing regions is presented below (Table 7, Figure 9), derived from regional agro-climatic parameters following the FAO-56 dual crop-coefficient methodology. This spatial estimate should be understood as a model-based approximation constructed from published station-level climatic normals and standard crop coefficients, rather than a result of real-time satellite image processing; for operational deployment, integration with MODIS, Landsat or Sentinel-2 imagery through an energy-balance model such as SEBAL or METRIC is recommended as the next methodological step, and is proposed as a component of the field research programme in Section 8.

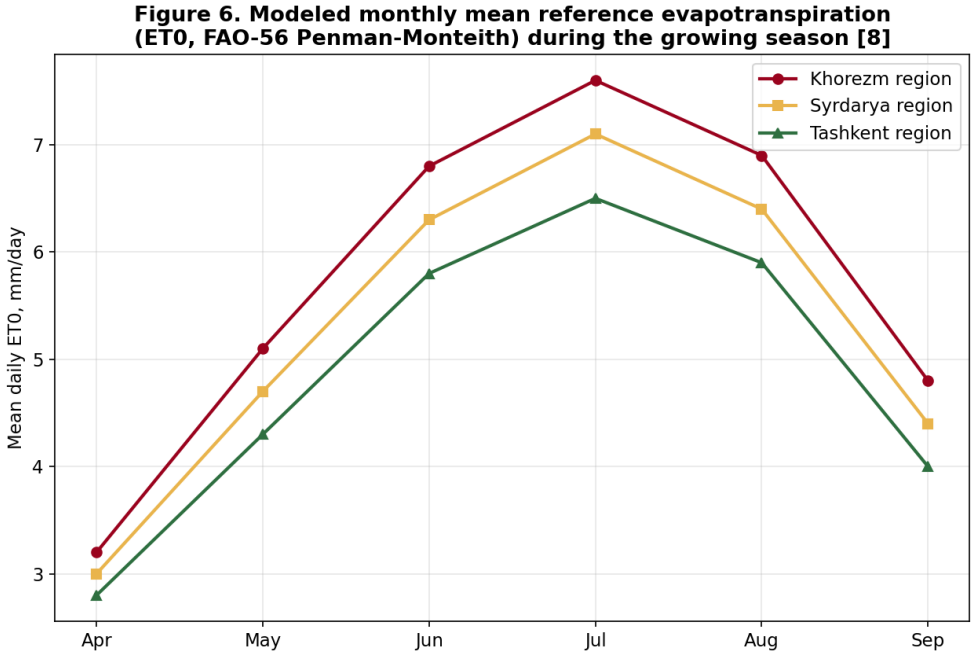

Figure 6. Modeled monthly mean reference evapotranspiration (ET0, FAO-56 Penman-Monteith) during the growing season [8]

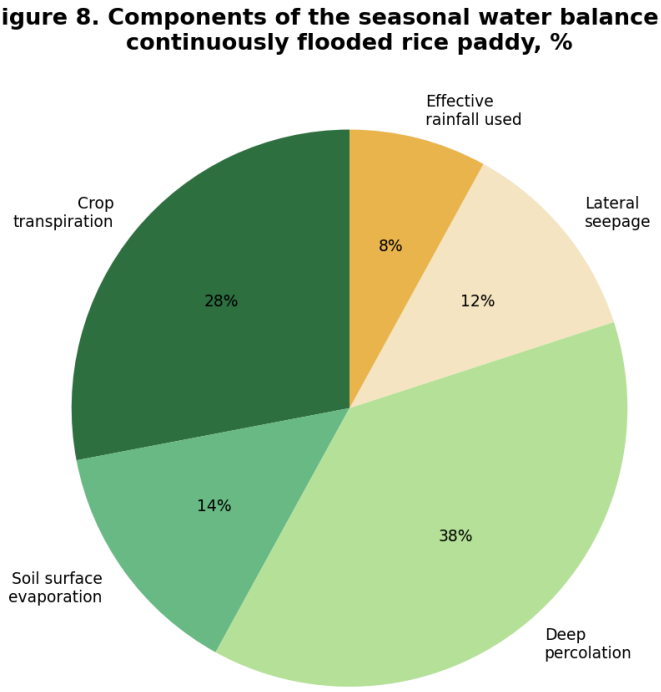

Figure 8. Components of the seasonal water balance in a continuously flooded rice paddy, %

Table 7. GIS-modeled regional ETc estimates for rice (seasonal totals)

Region	ET0, mm/season	Kc (rice, mean)	ETc, mm/season	ETc, m3/ha
Karakalpakstan	1010	1.17	1180	11,800
Khorezm	970	1.15	1120	11,200
Bukhara	940	1.15	1080	10,800
Syrdarya	880	1.13	990	9,900
Tashkent region	830	1.12	930	9,300
Fergana valley	860	1.12	960	9,600

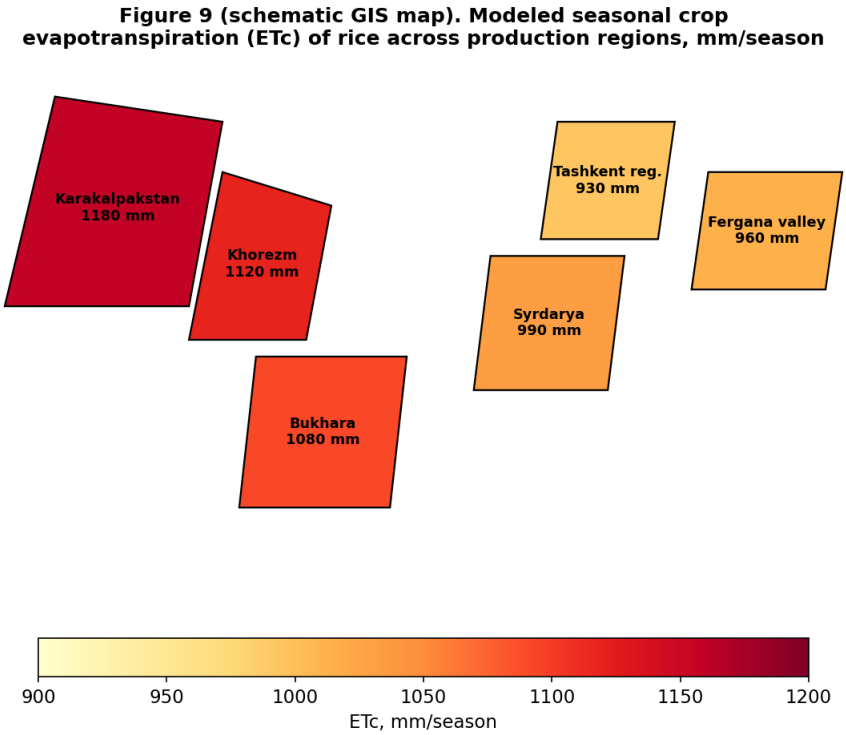

Figure 9 (schematic GIS map). Modeled seasonal crop evapotranspiration (ETc) of rice across production regions

The resulting spatial pattern shows the highest modeled ETc (1,120-1,180 mm/season) in Karakalpakstan and Khorezm, consistent with their hot, arid, near-Aral climate, and the lowest values (930-960 mm/season) in the comparatively cooler Tashkent region and Fergana valley. This spatial heterogeneity demonstrates that a single, nationally uniform irrigation norm cannot be equally efficient across all rice-growing regions and that norm-setting should be regionally differentiated.

8. PROPOSED RESEARCH METHODOLOGY

Direct measurement of water consumption: calibrated water gauges installed in canals, drains and paddy checks to record water depth and discharge throughout the growing season, following the field protocol applied on the Akdala rice system [7].

Comparative testing of irrigation regimes: continuous flooding (control), furrow irrigation, drip irrigation and AWD tested under identical agrotechnical conditions in replicated parallel field trials.

Incorporation of soil mechanical composition: particle-size analysis (sand/silt/clay fractions) at each trial site, with irrigation frequency and depth scheduled according to texture-specific water-holding capacity.

Monitoring of plant physiological indicators: LAI measured at each principal growth stage and related to biomass accumulation and yield components.

Assessment of ecological indicators: soil salinity, groundwater depth and, where feasible, methane and nitrous oxide flux measurement.

GIS and remote sensing: ET0/ETc estimated via the Penman-Monteith and Hargreaves-Samani methods, with spatial results mapped in a GIS environment and, in a subsequent phase, validated against satellite-derived (MODIS/Sentinel-2, SEBAL/METRIC) evapotranspiration products.

Comparative international analysis: results benchmarked against the Chinese, Kazakh and Indonesian experience reviewed above, to derive recommendations adapted to Uzbekistan's specific agro-ecological conditions.

CONCLUSION

Optimizing irrigation systems for rice cultivation in Uzbekistan carries strategic significance that extends beyond water conservation to the ecological rehabilitation of the Aral Sea basin. The Chinese experience demonstrates that irrigation norms differentiated by soil mechanical composition and regional climate can substantially reduce water use without technology transfer barriers; the Kazakh and broader Central Asian experience illustrates the institutional complexity of transboundary water management; and the Indonesian experience with drip irrigation and AWD confirms that water use and ecological burden can be reduced without a corresponding yield penalty. Incorporating physiological indicators such as LAI, together with GIS-based evapotranspiration analysis, enables a more precise understanding of how irrigation regime affects both the crop and the landscape scale. The multi-disciplinary methodology proposed here - integrating irrigation engineering, soil science, ecology, agronomy and GIS - is intended to generate scientifically grounded, practically applicable recommendations for rice cultivation under Uzbekistan's specific agro-ecological conditions.

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