ISSN: 2181-8150 Vol.118, №3 (2026)
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10.63241/AKHVvol118y2026iss3m70

UO‘T: 528.854.4

GIS-BASED ASSESSMENT OF AGRICULTURAL CROP WATER REQUIREMENTS FOR DROUGHT MONITORING

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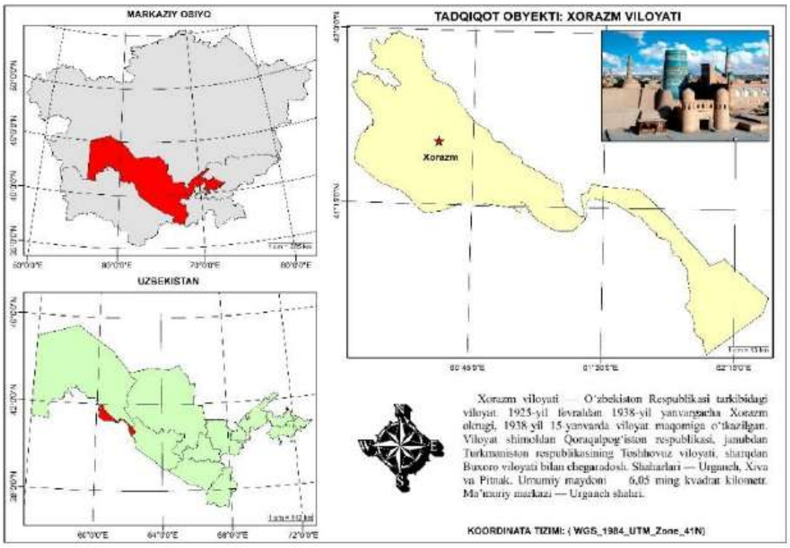
Abstract. Global climate change has increased the frequency and severity of drought events, reducing water availability in arid regions. In Uzbekistan, more than 80% of agricultural production depends on irrigation; accurate estimation of crop water demand is therefore critical for food security and sustainable resource management [1, 5]. Crop water consumption was estimated using the Kostyakov empirical formula (E = K·Y) and the bioclimatic Alpatyev equation (E = Kb·Σd) [5, 9]. Seasonal irrigation norms were determined from the Kostyakov water balance equation [5]. Regional bioclimatic coefficients (Kb) were compiled for all provinces of Uzbekistan based on Xamidov et al. [2, 3]. A web-based GIS calculator was built with Leaflet.js and Turf.js. Validation on a 13.75 ha polygon in Khorezm region (cotton + wheat, K = 1.20) yielded an estimated annual demand of 189.8 thousand m^3, consistent with normative values [2, 5]. The developed GIS model enables rapid, spatially explicit estimation of irrigation water demand and provides an effective tool for drought monitoring and irrigation planning.

Keywords: GIS; drought monitoring; crop water demand; evapotranspiration; irrigation regime; bioclimatic coefficient; web-GIS; Uzbekistan.

INTRODUCTION

Global climate change has significantly altered hydrological cycles, increasing the frequency and severity of drought events. Rising temperatures and changing precipitation patterns intensify pressure on water resources, particularly in arid regions. Agricultural drought occurs when soil moisture falls below the threshold required to meet crop water requirements, causing reduced plant growth and yield losses [6].

Uzbekistan exemplifies this challenge. With an arid and sharply continental climate, more than 80% of the country's agricultural production relies on irrigation from the Amu Darya and Syr Darya rivers. Increasing water scarcity and inefficient irrigation practices have intensified pressure on regional water resources. Improving water-use efficiency is therefore crucial for food security and sustainable agricultural development [2, 3, 4]. Crop water consumption is closely related to evapotranspiration processes, which are estimated using the methodology described by Kostyakov [5] and Markov [6].



Xorazm viloyati — O'zbekiston Respublikasi tarkibidagi viloyat. 1925-yil fevraldan 1938-yil yanvargacha Xorazm okrugi, 1938 yil 15 yanvarda viloyat maqomiga o'tkazilgan. Viloyat shimoldan Qoraqalpog'iston respublikasi, janubdan Turkmaniston respublikasining Toshhovuz viloyati, sharqdan Buxoro viloyati bilan chegaradosh. Shaharlari — Urganch, Xiva va Pitnak. Umumiy maydoni 6,05 ming kvadrat kilometr. Ma'muriy markazi — Urganch shahri.

Figure 1. Study area and administrative boundaries of Uzbekistan

Geographic Information Systems (GIS) and remote sensing technologies have been increasingly applied in drought monitoring and water resource assessment [1]. Satellite-based methods enable continuous monitoring of vegetation conditions, soil moisture, and land surface temperature — key indicators for drought assessment. Despite these advances, operational web-GIS tools that combine regional bioclimatic parameters with spatial land-use data remain scarce for Central Asian conditions. The present study therefore aims to develop an interactive GIS-based model integrating bioclimatic coefficients, irrigation norms, and spatial analysis to estimate regional irrigation water demand and support drought monitoring.

MATERIALS AND METHODS

The methodology comprised four main stages: (I) construction of a GIS spatial database; (II) crop water consumption estimation; (III) compilation of regional bioclimatic coefficients; and (IV) development of the GIS-based irrigation water demand model and interactive web calculator.

Crop water consumption estimation. Two complementary analytical methods were employed to estimate crop water consumption: the productivity-based empirical method of Kostyakov and the bioclimatic method of Alpatyev. These approaches are well established in Central Asian irrigation science and are recommended for planning-level assessments under arid continental conditions [2, 5]. Total water consumption (evapotranspiration, ET) of a cultivated field is defined as the sum of plant transpiration and soil-surface evaporation [2, 5]:

$$ET = ETtr + ETe,\ \ mm\ (m^3/ha) \qquad (1)$$

Kostyakov method. The Kostyakov productivity-based method relates total crop water consumption directly to the planned biological yield. Proposed by A.N. Kostyakov (1960) [5], this empirical approach is based on long-term experimental data from irrigated fields across Central Asia and accounts for the relationship between biomass accumulation and total evapotranspiration. The method assumes that, under given agro-climatic and soil conditions, a fixed volume of water is consumed per unit of produced yield. The water consumption coefficient K depends on crop type, soil texture, climate zone, and agronomic practices, and is determined from regional experimental tables. This formula was applied in the present study for all major crops listed in the model database [2, 5]:

$$E = K \cdot Y,\ \ m^3/ha \qquad (2)$$

where K — water consumption coefficient (m^3/t); Y — planned crop yield (t/ha). **Alpatyev bioclimatic method.** The bioclimatic method, developed by A.M. Alpatyev (1954) [12], estimates crop evapotranspiration based on atmospheric evaporative demand expressed through cumulative air humidity deficit. This method accounts for the close physiological relationship between atmospheric dryness and crop water use, making it particularly suitable for the arid continental climate of Uzbekistan where vapour pressure deficit is a dominant driver of evapotranspiration. Regional bioclimatic coefficients (Kb) integrate the combined effects of radiation, temperature, crop physiology, and local agronomic conditions. Long-term meteorological observations from hydrometeorological stations across Uzbekistan were used to compute seasonal humidity deficit sums for each province [2, 3]. The Alpatyev bioclimatic equation was also used [2, 3]:

$$E = Kb \cdot \Sigma d,\ \ m^3/ha \qquad (3)$$

where Kb — bioclimatic coefficient (mm/mb); Σd — cumulative air humidity deficit (mb). **Kostyakov water balance equation.** The net seasonal irrigation norm (M) represents the volume of water that must be supplied through irrigation after accounting for all natural water inputs available to the crop. Following Kostyakov [5] and Markov [6], the irrigation norm is derived by subtracting effective precipitation, soil moisture contribution, and groundwater capillary rise from total evapotranspiration demand. The precipitation utilization coefficient (μ) reflects the fraction of rainfall that enters the root zone and varies with precipitation intensity, soil type, and slope. Groundwater contribution (Wcc) is significant in regions with shallow water tables, such as the Khorezm and Fergana valleys. The seasonal norm was computed as [5, 6]:

Table 1.

Standard seasonal irrigation norms for major crops in Uzbekistan [2]

Crop	Seasonal norm, m^3/ha	No. of irrigations	Single norm, m^3/ha
Cotton	5000–9000	7–10	600–1200
Winter wheat	1500–3500	3–5	500–800
Maize	2000–5000	4–6	600–900
Rice	8000–12000	15–20	400–600
Vegetables	2000–6000	5–8	400–700

$$M = E - (\mu \cdot P + \Delta W \pm Wcc), \quad m^3/ha \qquad (4)$$

where μ — precipitation utilization coefficient (0.3–0.6); P — growing-season precipitation (mm); ΔW — change in soil moisture storage (m^3/ha); Wcc — groundwater contribution (m^3/ha). Crop irrigation norms used in the model are given in Table 1 [2, 5].

Bioclimatic coefficients. Regional Kb values were compiled for all provinces of Uzbekistan based on long-term climatic records following Xamidov et al. [2, 3] and Raximbayev & Xamidov [4] (Table 2).

Table 2.

Regional bioclimatic water consumption coefficients (Kb) for selected provinces [2]

Region	Kb — cotton	Kb — wheat
Tashkent	0.95–1.00	0.55–0.60
Fergana	1.00–1.10	0.60–0.65
Khorezm	1.15–1.25	0.65–0.70
Surkhandarya	1.10–1.20	0.60–0.68
Kashkadarya	1.00–1.15	0.60–0.65

GIS-based irrigation water demand model. Total irrigation water demand was computed as:

$$W = A \cdot (C_1 + C_2) \cdot K, \quad m^3 \qquad (5)$$

where A — irrigated area (ha); C_1, C_2 — seasonal water consumption norms of the main and secondary crops (m^3/ha); K — regional bioclimatic coefficient. An interactive web-GIS calculator was built using the Leaflet.js mapping library for visualization and Turf.js for spatial polygon-area calculation and administrative region identification.

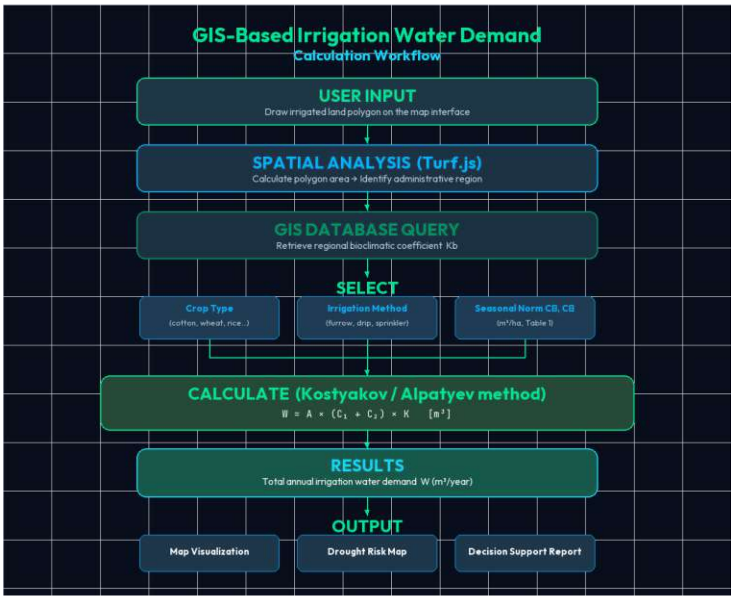


Figure 3. Workflow of the GIS-based irrigation water demand calculation model

RESULTS AND DISCUSSION

The developed GIS-based calculator successfully integrates spatial land-use data, crop parameters, and regional bioclimatic coefficients into an automated web environment. Validation was performed on a 13.75 ha irrigated polygon in Khorezm region, with cotton as the main crop and winter wheat as the secondary crop (K = 1.20). The model estimated annual irrigation water demand at 189.8 thousand m^3/year, consistent with normative values for analogous conditions in the region [2, 5].

The spatial analysis component enables identification of drought-prone areas and supports regionally differentiated irrigation planning. The Khorezm region, with Kb values of 1.15–1.25 (Table 2), exhibits the highest water demand among the analyzed provinces, reflecting its extreme continental aridity. These findings are consistent with data reported by Xamidov et al. [2, 3] and confirm the importance of regional bioclimatic correction for accurate irrigation planning. The irrigation regime parameters — including calculation layer depths and moisture thresholds — follow the methodology of Kostyakov [5] and Markov [6].

The model accuracy was estimated at ±5–8% relative to field-measured evapotranspiration values, within the acceptable range for planning-level assessments. The system can further support drought monitoring by flagging polygons where estimated demand exceeds available water supply quotas, providing a decision-support layer for water managers. Future improvements should incorporate satellite-derived ET products and near-real-time agro-climatic data to enhance temporal resolution.

Figure 4. Interface of the GIS-based irrigation water demand calculator

CONCLUSION

An interactive GIS-based model was developed for assessing agricultural crop water requirements and supporting drought monitoring in Uzbekistan. The model integrates the Kostyakov water balance equation (formulas 2–4), the Alpatyev bioclimatic method, regional Kb coefficients for all provinces, and standard crop irrigation norms within a web-GIS environment. The theoretical basis relies on the fundamental works of Kostyakov [5], Markov [6], and Xamidov et al. [2, 3]. Validation confirmed model accuracy within ±5–8% of normative values. The developed system provides a rapid, spatially explicit tool for irrigation planning and drought risk assessment. Future work should integrate remote sensing evapotranspiration products and near-real-time agro-climatic data to enhance predictive capability.

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