

SATELLITE-DRIVEN MONITORING OF AGRICULTURAL WATER USE FOR CLIMATE-RESILIENT GOVERNANCE IN UZBEKISTAN

SUIVI SATELLITAIRE DE L'UTILISATION DE L'EAU AGRICOLE POUR UNE GOUVERNANCE RÉSILIENTE AU CLIMAT EN OUZBÉKISTAN

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ABSTRACT

Water scarcity is becoming an increasingly critical challenge in Central Asia due to climate change, glacier retreat, population growth, and increasing agricultural demand. In Uzbekistan, irrigated agriculture remains the dominant consumer of available water resources and plays a strategic role in national food production and economic development. Improving water allocation and irrigation efficiency therefore requires reliable and scalable approaches for monitoring actual water consumption.

This study presents a satellite-driven system developed for monitoring agricultural water use across approximately one million hectares of irrigated land in Uzbekistan. The system was implemented in Samarkand, Kashkadarya, and Fergana regions during 2024–2025 and is planned for expansion into Syrdarya region in 2026.

The methodology combines open-access satellite imagery from Sentinel-2 and Landsat missions with geospatial analysis and the Surface Energy Balance Algorithm for Land (SEBAL) to estimate actual evapotranspiration (ETa), representing real crop water consumption. Land Surface Temperature (LST) was applied as a key parameter for improving estimation accuracy.

In parallel, extensive GIS-based infrastructure digitization was performed, including more than 67,000 km of irrigation networks, over 11,000 hydraulic structures, and linkage of more than one million hectares of agricultural land to irrigation infrastructure.

The results identified zones with water deficit, excessive water use, and water stress conditions. Water consumption analysis across crop categories demonstrated significant spatial variation between wheat and cotton production systems. The developed approach provides objective and spatially detailed information for irrigation planning, drought response, and climate adaptation.

The study demonstrates that integration of satellite observations and geospatial technologies provides an operational and scalable framework for climate-resilient water governance in irrigated agriculture

Keywords: Satellite-driven monitoring; Agricultural water use; Water scarcity; Actual water consumption; Irrigation networks.

RÉSUMÉ

La pénurie d'eau devient un enjeu de plus en plus critique en Asie centrale sous l'effet du changement climatique, du recul des glaciers, de la croissance démographique et de l'augmentation de la demande agricole. En Ouzbékistan, l'agriculture irriguée demeure le principal consommateur des ressources en eau disponibles et joue un rôle stratégique dans la production alimentaire nationale et le développement économique. L'amélioration de l'allocation de l'eau et de l'efficacité de l'irrigation exige donc des approches fiables et évolutives pour suivre la consommation réelle d'eau.

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Cette étude présente un système satellitaire mis au point pour suivre l'utilisation de l'eau agricole sur environ un million d'hectares de terres irriguées en Ouzbékistan. Le système a été déployé dans les régions de Samarcande, de Kachkadaria et de Ferghana en 2024–2025, et son extension à la région de Syr-Daria est prévue en 2026.

La méthodologie combine des images satellitaires en accès libre provenant des missions Sentinel-2 et Landsat avec l'analyse géospatiale et l'algorithme de bilan énergétique de surface des terres (SEBAL), afin d'estimer l'évapotranspiration réelle (ET_a), qui représente la consommation réelle d'eau par les cultures. La température de surface des terres (LST) a été utilisée comme paramètre clé pour améliorer la précision des estimations.

Parallèlement, une vaste numérisation des infrastructures dans un SIG a été réalisée, portant notamment sur plus de 67 000 km de réseaux d'irrigation et plus de 11 000 ouvrages hydrauliques, ainsi que sur le rattachement de plus d'un million d'hectares de terres agricoles aux infrastructures d'irrigation.

Les résultats ont permis de repérer les zones en déficit hydrique, en surconsommation d'eau et soumises au stress hydrique. L'analyse de la consommation d'eau par catégorie de cultures a révélé d'importantes variations spatiales entre les systèmes de production du blé et du coton. L'approche mise au point fournit des informations objectives et spatialement détaillées pour la planification de l'irrigation, la réponse aux sécheresses et l'adaptation au climat.

L'étude montre que l'intégration des observations satellitaires et des technologies géospatiales fournit un cadre opérationnel et évolutif pour une gouvernance de l'eau résiliente au climat dans l'agriculture irriguée.

Mots clés : Suivi satellitaire; Utilisation de l'eau agricole; Pénurie d'eau; Consommation réelle d'eau; Réseaux d'irrigation

1. INTRODUCTION

Central Asia is among the regions most vulnerable to increasing water stress under changing climate conditions. Rising air temperatures, glacier retreat in upstream river basins, changing precipitation patterns, and increasing evapotranspiration rates are intensifying pressure on regional water resources. These challenges directly affect irrigated agriculture, which remains the largest consumer of freshwater resources across the region.

In Uzbekistan, agriculture accounts for the majority of national water consumption and plays an important role in ensuring food security, rural livelihoods, and export-oriented production. Traditional approaches to irrigation management are often constrained by limited field observations, uneven monitoring coverage, and delayed reporting mechanisms, reducing the ability to respond effectively during drought periods and water shortages.

Recent advances in Earth Observation technologies provide opportunities to transition toward data-driven water governance. Satellite-based monitoring enables continuous and objective assessment of agricultural conditions over large territories while reducing dependency on extensive ground measurement infrastructure.

Among remote sensing approaches, evapotranspiration-based monitoring has become increasingly important because evapotranspiration represents actual crop water consumption and serves as a direct indicator of water use efficiency. Surface energy balance methods allow evapotranspiration to be estimated using satellite observations combined with meteorological and geospatial datasets.

This study presents implementation of a satellite-driven monitoring system designed to evaluate agricultural water consumption and support climate-resilient governance in Uzbekistan. The system combines satellite-derived evapotranspiration estimates, irrigation infrastructure mapping, and GIS-

based analysis to provide decision support for water allocation and irrigation performance assessment.

The study focuses on three regions of Uzbekistan—Samarkand, Kashkadarya, and Fergana—covering approximately one million hectares of irrigated land. The objectives were to:

- estimate actual crop water consumption using satellite observations;
- identify areas affected by water deficit, water stress, and excessive irrigation;
- analyze water use across major agricultural crops;
- integrate irrigation infrastructure into geospatial monitoring workflows;
- support adaptive and evidence-based water management practices.

2. STUDY AREA

The study was conducted in three major agricultural regions of Uzbekistan, namely Samarkand, Kashkadarya, and Fergana regions, which represent key irrigated agricultural zones of the country. These regions are characterized by intensive irrigation-based farming systems, dominated by cotton, wheat, maize, rice, alfalfa, and horticultural crops.

The total study area covers approximately one million hectares of irrigated agricultural land, representing a significant portion of the national irrigated landscape. These regions experience semi-arid climatic conditions, high summer temperatures, and increasing variability in water availability due to upstream hydrological changes and climate-induced glacier retreat.

The selected regions differ in terms of irrigation infrastructure density, water availability, and cropping patterns, making them suitable for comparative analysis of agricultural water consumption and irrigation efficiency under varying hydrological conditions.

Table 1. Overview of study regions and datasets

Parameter	Value
Study regions	Samarkand, Kashkadarya, Fergana
Study period	2024–2025
Expansion	Syrdarya (2026)
Area analyzed	~1 million ha
Irrigation network	67,000 km
Hydraulic structures	11,000
Satellite sources	Sentinel-2, Landsat 8–9
ET model	SEBAL

3. MATERIALS AND METHODS

3.1 Satellite Data

This study utilizes multi-source Earth Observation data from the Sentinel-2 (ESA) and Landsat (NASA/USGS) satellite missions to support large-scale agricultural water monitoring and evapotranspiration modeling.

The Sentinel-2 mission provides high-resolution multispectral imagery with spatial resolution up to 10 meters and a revisit frequency of 5 days. It includes visible, near-infrared (NIR), and shortwave infrared (SWIR) spectral bands, which are essential for vegetation monitoring, crop classification, and

derivation of vegetation indices such as NDVI (Normalized Difference Vegetation Index). These products are used to assess crop conditions and spatial variability in vegetation development.

The Landsat program (Landsat 8 and Landsat 9) provides long-term Earth observation data with moderate spatial resolution (30 meters) and thermal infrared (TIR) bands, which are critical for estimating Land Surface Temperature (LST). LST is a key variable for surface energy balance modeling and plays an important role in estimating evapotranspiration through the SEBAL approach.

In this study, satellite imagery from both missions was used in a complementary manner. Sentinel-2 data were primarily applied for high-resolution vegetation analysis and crop mapping, while Landsat thermal data were used for surface temperature retrieval and energy balance computation.

All satellite data were processed within a geospatial environment (GIS), where atmospheric correction, cloud masking, and radiometric calibration were applied to ensure data consistency and accuracy. The combination of multi-temporal and multi-source satellite observations enabled continuous monitoring of agricultural conditions throughout the growing season.

This integrated satellite dataset forms the foundation for spatially explicit estimation of actual evapotranspiration (ET_a), enabling scalable and consistent monitoring of agricultural water consumption across large irrigated areas in Uzbekistan.

3.2 Evapotranspiration Estimation (SEBAL)

Actual evapotranspiration (ET_a) was estimated using the Surface Energy Balance Algorithm for Land (SEBAL), a physically based remote sensing model that derives water consumption from satellite-observed land surface energy fluxes.

SEBAL is based on the surface energy balance equation:

- **$R_n = G + H + LE$**
- where: **R_n** = net radiation
- **G** = soil heat flux
- **H** = sensible heat flux
- **LE** = latent heat flux (evapotranspiration component)

In this framework, evapotranspiration is calculated as the residual energy component (LE), representing the energy used for water vaporization from soil and vegetation surfaces.

The model integrates satellite-derived biophysical parameters such as vegetation indices, surface reflectance, and Land Surface Temperature (LST), which is a key variable for estimating sensible heat flux and surface energy partitioning.

The SEBAL implementation in this study follows a multi-step processing chain, including: estimation of surface albedo and net radiation (R_n), calculation of soil heat flux (G), derivation of aerodynamic resistance parameters, computation of sensible heat flux (H), and final estimation of latent heat flux (LE) as actual evapotranspiration (ET_a).

This approach enables spatially distributed estimation of crop water consumption without requiring dense ground meteorological measurements, making it suitable for large-scale irrigation monitoring in data-scarce regions.

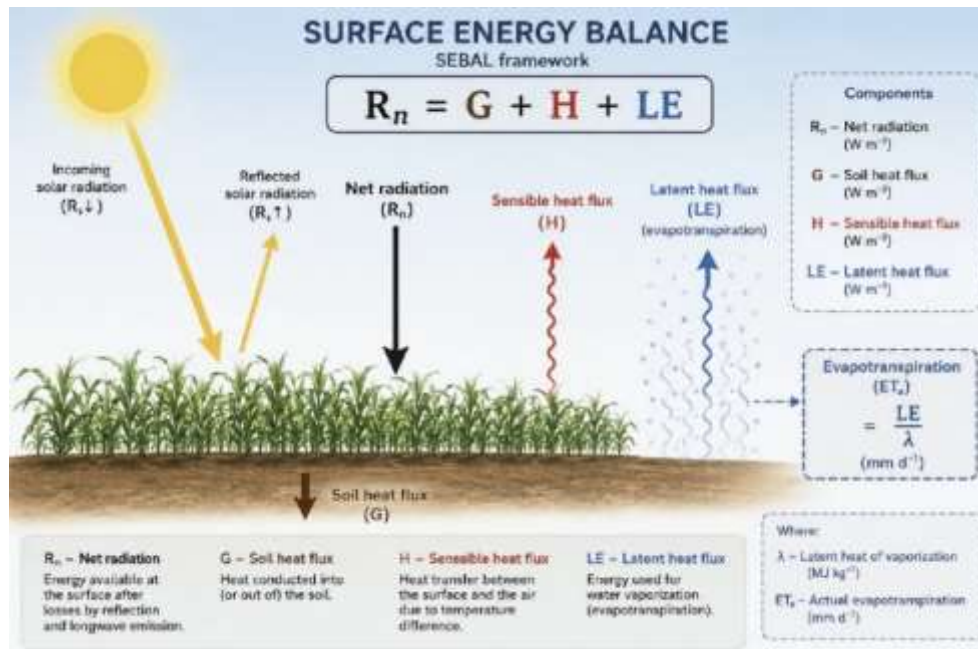


Figure 1. Surface energy balance scheme for evapotranspiration estimation using SEBAL model

3.3 Land Surface Temperature (LST)

Land Surface Temperature (LST) is a key parameter in the SEBAL model and plays a central role in estimating sensible heat flux and surface energy partitioning. LST is derived from thermal infrared satellite observations (primarily Landsat data) and reflects the thermal condition of the land surface, which is directly linked to crop water stress and evapotranspiration dynamics.

In this study, the SEBAL model was implemented in Python programming environment, which enabled full automation of the processing chain, including the derivation of biophysical parameters and the estimation of actual evapotranspiration (ET_a) at large spatial scales. The Python-based implementation significantly improved workflow efficiency and allowed systematic processing of multi-temporal satellite datasets.

A key step in the SEBAL workflow is the identification of “hot” and “cold” pixels, which serve as anchor pixels for calibrating the near-surface temperature gradient (dT) between two reference conditions. This temperature difference is one of the fundamental parameters in the SEBAL energy balance formulation.

3.4 In the SEBAL framework

Cold pixels are typically selected over water bodies or areas with dense and well-irrigated vegetation, representing maximum evapotranspiration conditions;

Hot pixels are selected over dry bare soil surfaces with minimal vegetation cover, representing minimum evapotranspiration conditions.

In this implementation, cold pixels were automatically identified based on the distribution of surface temperature derived from Landsat thermal bands, while hot pixels were determined using NDVI-based masking and temperature thresholds to ensure representative dry surface conditions.

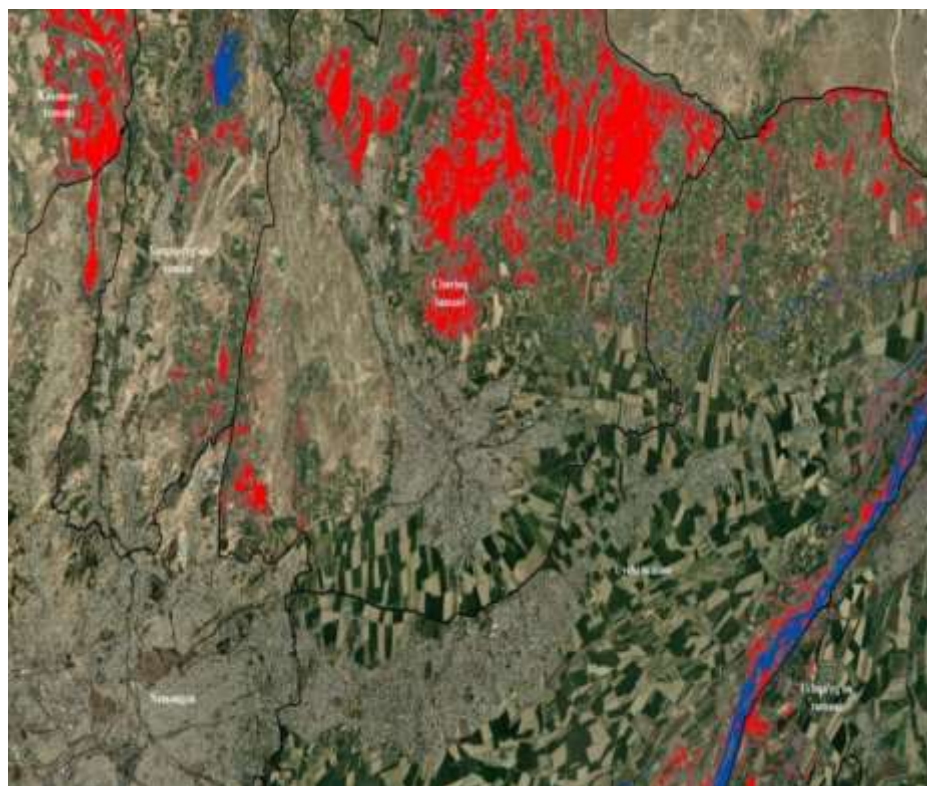


Figure 2. Automatically identified “hot” and “cold” pixels using SEBAL model applied to Landsat 8 imagery (14 June 2024, Fergana region). Cold pixels are located over water bodies, while hot pixels correspond to dry bare soil areas.

3.5 GIS-Based Irrigation Infrastructure Mapping

To support satellite-based assessment of agricultural water consumption, a comprehensive GIS-based irrigation infrastructure database was developed for the three pilot regions of Uzbekistan—Samarkand, Kashkadarya, and Fergana regions.

The geospatial database was created through integration of existing cartographic materials, remote sensing interpretation, and GIS-based data processing and includes:

- more than 67,000 km of irrigation network channels;
- over 11,000 hydraulic infrastructure objects;
- spatial linkage of more than 1 million hectares of irrigated agricultural land to the corresponding irrigation system.

The developed geospatial framework enabled establishment of direct relationships between agricultural fields and water delivery infrastructure, allowing water consumption analysis not only at field scale but also within the context of irrigation network operation.

This integration significantly expands the analytical capability of satellite-derived evapotranspiration assessment by enabling evaluation of irrigation performance, identification of spatial inequalities in water distribution, and detection of inconsistencies between supplied and consumed water volumes. In addition, the developed GIS environment allows identification of areas with water deficit, excessive water use, and limited water accessibility within irrigation systems, supporting more targeted and evidence-based water management decisions.

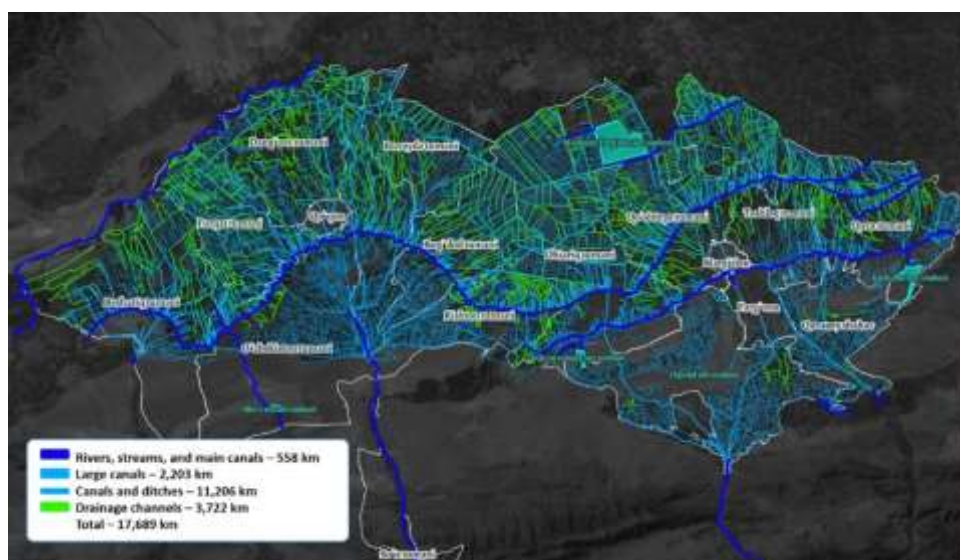


Figure 3. Example of GIS-based irrigation infrastructure mapping and agricultural field linkage in Fergana region.

3.6 Water Stress and Irrigation Inefficiencies

The spatial analysis of satellite-derived actual evapotranspiration (ET_a) revealed substantial heterogeneity in irrigation performance and agricultural water availability across the study area. Based on the relationship between estimated crop water consumption and expected irrigation conditions, three major categories of irrigation status were identified.

- **Water deficit zones (20%)** — areas where actual evapotranspiration remained below crop water requirements, indicating insufficient irrigation supply and reduced water availability for crop development. These conditions increase the risk of lower productivity and reduced resilience under elevated temperature conditions.
- **Over-irrigated zones (15%)** — areas where water consumption exceeded optimal crop demand, suggesting excessive irrigation application and reduced water-use efficiency. Analysis showed that these zones are predominantly located in areas situated close to irrigation water sources and main delivery canals, where water accessibility is higher.
- **Water stress zones (17%)** — areas where crops experienced combined effects of high atmospheric evaporative demand and limited water availability, resulting in suppressed evapotranspiration relative to climatic conditions. These zones were predominantly observed in remote parts of irrigation systems where water delivery becomes less stable and irrigation volumes are insufficient to satisfy crop requirements.

The identified spatial distribution demonstrates clear inequalities in water allocation within irrigation systems. While areas located near water intake points tend to receive excessive irrigation volumes, downstream and remote agricultural zones experience increasing water scarcity and crop stress.

These findings highlight systemic challenges in irrigation management and confirm the need for continuous monitoring tools capable of evaluating actual water consumption at field scale. Integration of satellite-derived evapotranspiration with irrigation infrastructure mapping provides an objective basis for improving water distribution efficiency and supporting climate-resilient irrigation governance.



Figure 4. Spatial distribution of irrigation performance categories derived from evapotranspiration analysis: water stress zones (red, 17%), water deficit zones (dark orange, 20%), and over-irrigated zones (blue, 15%) within the study area.

3.7 Crop-Specific Water Consumption

Satellite-based crop classification combined with SEBAL-derived actual evapotranspiration (ETA) enabled quantitative assessment of agricultural water consumption across major crop types and regions. The analysis focused on dominant irrigated crops and revealed significant differences in water use intensity depending on crop characteristics, irrigation practices, and local water availability.

The results demonstrate that wheat consistently exhibited lower water consumption compared to cotton across all study regions, reflecting lower seasonal evapotranspiration demand and different irrigation requirements. In contrast, cotton showed substantially higher water consumption, confirming its status as one of the most water-intensive agricultural crops cultivated under irrigated conditions in Uzbekistan.

Spatial variability of crop water consumption was observed not only between crop types but also across regions, indicating differences in climatic conditions, irrigation performance, and water accessibility within irrigation systems.

The estimated seasonal crop water consumption values are presented in Table 2

Table 2. Estimated seasonal water consumption of major crops by region

Region	Wheat (thousand m ³ /ha)	Cotton (thousand m ³ /ha)
Samarkand	1.4	6.2
Kashkadarya	2.0	6.1
Fergana	2.1	5.5

The results indicate relatively stable water consumption patterns for cotton across regions, while wheat demonstrated greater regional variability. The highest wheat water consumption was observed in Fergana region, whereas the lowest values were recorded in Samarkand region. Cotton maintained consistently high seasonal water demand in all analyzed territories.

These findings demonstrate the value of satellite-derived evapotranspiration for generating objective crop-specific water consumption indicators and supporting more efficient irrigation planning under increasing climate pressure

4. FUTURE DEVELOPMENT

Future development of the system will focus on increasing the accuracy, reliability, and operational applicability of satellite-based agricultural water monitoring through integration of field measurements and advanced validation approaches.

In 2026, a ground truth measurement network is planned to be deployed in the Kashkadarya region to support calibration and validation of satellite-derived evapotranspiration estimates. The monitoring infrastructure will include field instrumentation designed to directly measure components influencing crop water consumption and surface energy exchange.

The planned measurement system will include sensors for:

actual evapotranspiration monitoring, soil moisture measurement, air temperature and relative humidity observation, incoming and outgoing solar radiation monitoring, surface temperature registration, meteorological parameter collection required for energy balance calculations.

Ground measurements will provide continuous in-situ observations and will be used as reference data for validating SEBAL-derived evapotranspiration outputs and improving estimation accuracy under local climatic and irrigation conditions.

The implementation of ground truth observations will also support refinement of Land Surface Temperature (LST)-based modeling approaches, improve automatic calibration procedures for hot and cold pixel selection, and reduce uncertainty in satellite-derived water consumption estimates. The long-term objective is to transform the developed framework into an operational monitoring and decision-support system capable of continuous assessment of irrigation performance and agricultural water consumption at regional scale. Such integration of satellite observations with field-based measurements will strengthen climate-resilient water governance and improve adaptive irrigation management in water-scarce regions.

Although large-scale validation is planned through deployment of ground truth sensors in 2026, preliminary quality control was performed through consistency analysis across multi-temporal observations and comparison with expected crop water consumption ranges reported in literature.

5. INTEGRATED SATELLITE-BASED WATER GOVERNANCE FRAMEWORK

The developed approach combines Earth Observation data, evapotranspiration modeling, GIS infrastructure analysis, and field validation into a unified decision-support framework for agricultural water management.

The workflow begins with acquisition of satellite imagery and extraction of biophysical parameters including vegetation indices and Land Surface Temperature (LST). These inputs are processed through the SEBAL model to estimate actual evapotranspiration and crop water consumption.

The resulting outputs are integrated with GIS-based irrigation infrastructure datasets, enabling spatial analysis of irrigation performance, detection of water stress and excessive irrigation zones, and evaluation of water allocation efficiency.

Ground truth measurements planned for future implementation will support calibration and validation of satellite-derived estimates and improve operational reliability. The integrated framework provides decision support for climate-resilient irrigation governance through continuous monitoring and objective assessment of water use at regional scale.

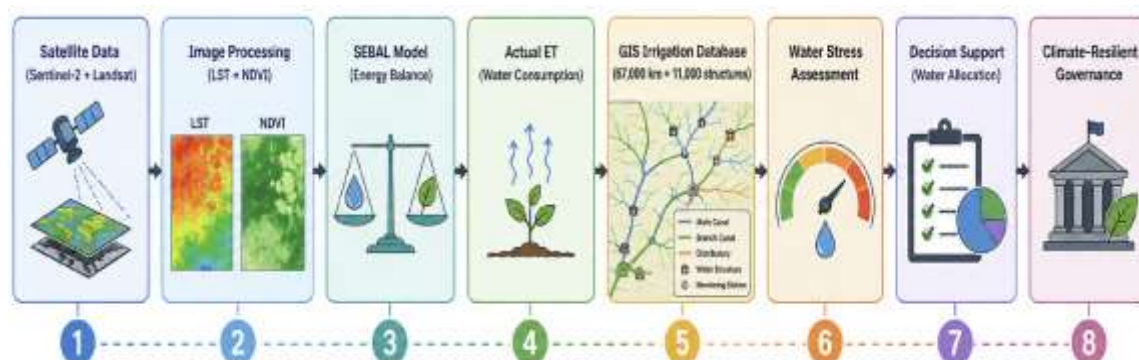


Figure 5. Integrated workflow of satellite-driven agricultural water governance in Uzbekistan.

6. CONCLUSIONS

This study demonstrates the practical applicability of satellite-driven monitoring for improving agricultural water governance under increasing climate pressure in Uzbekistan.

By integrating Earth Observation data, SEBAL-based evapotranspiration modeling, and GIS-based irrigation infrastructure analysis, the developed system enabled objective assessment of actual agricultural water consumption across approximately one million hectares of irrigated land in Samarkand, Kashkadarya, and Fergana regions.

The use of Sentinel-2 and Landsat imagery, combined with automated processing workflows and Land Surface Temperature (LST) analysis, provided consistent estimation of actual evapotranspiration and allowed identification of spatial patterns of irrigation performance.

The study demonstrated that agricultural water consumption varies significantly across crop types and regions, with cotton showing consistently higher seasonal water demand than wheat. The analysis also identified zones affected by water deficit (20%), water stress (17%), and over-irrigation (15%), revealing spatial inequalities in water distribution across irrigation systems. Areas located near water delivery sources showed increased occurrence of excessive irrigation, while remote areas demonstrated higher exposure to water shortages and crop stress.

The integration of evapotranspiration monitoring with digitized irrigation infrastructure—including more than 67,000 km of irrigation networks, 11,000 hydraulic structures, and 1 million hectares of linked agricultural land—provided additional capability for evaluating water allocation efficiency and supporting evidence-based irrigation management.

Future implementation of field-based ground truth measurements will further strengthen calibration and validation of satellite-derived estimates and support operational deployment of the developed framework.

The results confirm that satellite-based agricultural water monitoring represents a scalable and cost-effective approach for improving irrigation efficiency, strengthening climate resilience, and supporting sustainable water governance in Uzbekistan and other water-scarce regions.

The developed framework enabled assessment of water use across approximately 1 million hectares and identification of irrigation anomalies affecting more than half of analyzed territories.

REFERENCES

- Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper No. 56. Rome.
- Allen, R.G., Tasumi, M., and Trezza, R. 2007. Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Model. *Journal of Irrigation and Drainage Engineering*, 133(4), 380–394.
- Bastiaanssen, W.G.M., Menenti, M., Feddes, R.A., and Holtslag, A.A.M. 1998. A remote sensing surface energy balance algorithm for land (SEBAL): Part 1. Formulation. *Journal of Hydrology*, 212–213, 198–212.
- Bastiaanssen, W.G.M., Noordman, E.J.M., Pelgrum, H., Davids, G., Thoreson, B.P., and Allen, R.G. 2005. SEBAL Model with remotely sensed data to improve water-resources management under actual field conditions. *Journal of Irrigation and Drainage Engineering*, 131(1), 85–93.
- Broner, I. and Law, R.R.P. 1992. Water balance for irrigation using ET input. *ICID Bulletin*, 41(2), 173–182.
- Gao, B.C. 1996. NDVI—A normalized difference vegetation index for remote sensing of vegetation. *Remote Sensing of Environment*, 58(3), 257–266.
- Senay, G.B., Bohms, S., Singh, R.K., Gowda, P.H., Velpuri, N.M., Alemu, H., and Verdin, J.P. 2013. Operational evapotranspiration mapping using remote sensing and weather datasets. *Remote Sensing*, 5(10), 4993–5010.
- United Nations. 2023. The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water. Paris.
- USGS. 2024. Landsat 8–9 Data Users Handbook.
- European Space Agency (ESA). 2024. Sentinel-2 User Handbook.