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# ASSESSMENT AND ANALYSIS OF COTTON DEVELOPMENT GROWTH IN PIVOT IRRIGATION AREAS USING SATELLITE IMAGERY

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***Abstract***

*The management of irrigation and the proper utilization of water resources are essential for enhancing agricultural output and maintaining the environment. Cotton fields irrigated with pivot systems are especially vulnerable to water stress and uneven distribution, both of which have a direct impact on yield. In this context, effective and dependable monitoring of water conditions and vegetation health is crucial for enhancing agricultural decision-making. The research shown that the integration of Sentinel-2 multispectral satellite data with water-sensitive spectral indices is exceptionally successful in monitoring water regimes, moisture dynamics and stress processes in pivot fields. The NDMI, NDWI and LSWI indices are essential for evaluating irrigation cycles and the soil-plant water balance, whereas the GNDVI and SWIR-based indices facilitate the early detection of vegetation responses and water stress. Stress maps indicated that the majority of the pivot fields exhibit a good condition of vegetation, with low and non-systematic water stress, whereas the primary risk factor identified is controlled nutritional stress. This methodology establishes an effective scientific and practical foundation for the early identification of water stress and the optimization of moisture management.*

***Keywords****: pivot, cotton, vegetation index, satellite imagery, water stress.*

## Introduction

Cotton (Gossypium hirsutum L) is a plant of strategic importance in the world agricultural system, contributing to fiber and oilseed production and playing a crucial role in the textile industry, animal husbandry, oil, medical and defense industries. Nitrogen is essential for the photosynthetic process and the proper growth of this plant, which is very susceptible to environmental conditions and agricultural management practices. The optimum nitrogen fertilization adjustment improves plant productivity, both deficit and excess may affect efficiency. Cotton is extensively grown in the Aran and Karabakh economic regions of Azerbaijan and is also regarded as a strategic crop. Water supply, operational detection of stress factors and proper control of the irrigation regime are all very important for cotton production [1], [2]. Spatial monitoring of field-level moisture dynamics and stress variations remains a pressing scientific concern, despite the fact that pivot-type central circular irrigation systems improve irrigation efficiency [3]. Thus, cotton production needs to be monitored for nitrogen supply and irrigation to achieve sustainable growth and efficiency.

Over the past decade, the high spatial resolution (10–20 m) and short revisit period (5 days) of Sentinel-2 multispectral satellite imagery has facilitated the operational monitoring of plant growth, soil moisture metrics and stress phases [4]. Recent studies have proven the capability of continuous monitoring of water status in cotton plants by index techniques utilizing Sentinel-2 data. Additionally, the acute sensitivity of water indices (NDWI, LSWI, NDMI) to soil moisture and vegetation water content has been established [5], alongside the unique capability of NDMI for modeling soil moisture at the field scale [6]. LSWI exhibits a strong association with the overall water balance of the soil.

Previous researches have confirmed that remote sensing indices, such as GNDVI and SWIR, exhibit excellent sensitivity and scientific efficacy in the operational evaluation of water status and leaf moisture content in cotton plants during the growing season. The implementation of vegetation indices is a primary strategy for evaluating the health of cotton plants. GNDVI exhibits significant sensitivity in assessing chlorophyll content and nitrogen availability [7]. SWIR-based stress indicators are crucial for the early identification of phenomena such as leaf desiccation, moisture depletion and structural impairment [8].

Although these methods are commonly used in international practice, there is still a lack of adequately developed integrated real-time monitoring frameworks for pivot irrigation systems in Azerbaijan. These frameworks would combine both irrigation and physiological stress indices. The emphasis of numerous international studies on a singular spectral indicator complicates the differentiation of various stress variables affecting the cotton plant concurrently [9], [10]. An important scientific gap in the effective management of water resources is the lack of practical assessments of how irrigation regime and plant stress interact based on satellite data.

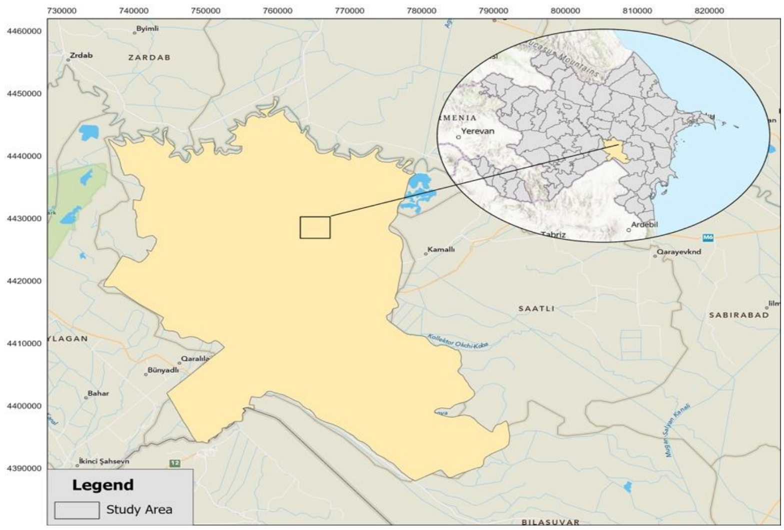
The objective of the study is to address this gap by proposing a multi-criteria rule-based model named "StressClass" which enables the differentiated identification of water stress and nitrogen stress. The intent is to develop a comprehensive real-time monitoring system for the field by integrating the study of irrigation indicators and stress indices (GNDVI, NDMI, SWIR_Stress) with Sentinel-2 data. The excellent spectral homogeneity (CV < 5%) of pivot irrigation systems in the dry-subtropical climate of the Mil-Mugan plain in Azerbaijan signifies the sustainability of technology irrigation under adverse climatic circumstances. This method facilitates the practical evaluation of moisture conditions, stress levels and vegetation indicators, while also optimizing irrigation management based on scientific principles.

## Methodology

This study used Sentinel-2 MSI (MultiSpectral Instrument) satellite images characterized by high spatial, spectral and temporal resolution as the data source. The Google Earth Engine (GEE) platform applied a dataset with less than 10% cloud cover that included data from both the Sentinel-2A and Sentinel-2B satellites [11]. The 5-day temporal resolution of the Sentinel-2A and 2B satellite constellation facilitated a more comprehensive and continuous time series study for the 2025 growing season (May–September). Data was processed using the median composite approach at 10-day intervals to produce stable images free of clouds.

The research area covers cotton fields implementing center pivot irrigation systems in the Mil-Mugan plain of Azerbaijan, within the Imishli district. This region is geographically situated between latitudes 39°94′ N and 39°99′ N, longitudes 48°06′ E and 48°14′ E (Figure 1). Imishli has a dry-subtropical climate with a high temperature potential and an extreme precipitation deficit during cotton season. The region's average annual precipitation is 268–292 mm and it has been dropping for decades [12]. Absolute maximum temperatures can reach +42-44°C during the summer months of July and August [13]. Operating monitoring of the irrigation regime in cotton fields is necessary due to the fact that evaporation is significantly higher than precipitation. Extreme temperatures supply the heat reserve needed for plant development, but current warming increases cotton's watering needs and physiological stress. The disparity between evaporation and precipitation needs the operational monitoring of the irrigation regime in cotton fields.

**Figure 1. Study Area.**




***Source:*** Figure showing the study area, prepared by the author.

**Table 1. Spectral indices for cotton plant physiological and moisture status.**

| Indices | Formula |
|---|---|
| NDMI | (NIR – SWIR1) / (NIR + SWIR1) |
| NDWI | (Green – NIR) / (Green + NIR) |
| LSWI | (NIR – SWIR2) / (NIR + SWIR2) |
| GNDVI | (NIR – Green) / (NIR + Green) |
| SWIR Stress | (SWIR1 - NIR) / (SWIR1 + NIR) |

***Source:*** The table was prepared by the author using standard remote sensing methodologies.

The precise digitization and vectorization of the contours of six separate pivot areas using ArcGIS Pro software verified the correctness of the spatial analysis. Mathematical algorithms based on Sentinel-2's spectral channels calculated target indices sensitive to biophysical indicators to quantify the cotton plant's water supply, tissue moisture balance and physiological development dynamics ***(table 1).*** Green (Band 3), NIR (Band 8), SWIR1 (Band 11) and SWIR2 (Band 12) refer to the respective spectral channels of the Sentinel-2 MSI sensor ***(table 2)***.

A pixel-based "Decision Tree" methodology was implemented to thoroughly evaluate the stress condition of cotton plants. This method relies on a combination of spectral indicators that indicate variations in water availability, photosynthetic activity and leaf morphology of cotton plants. Only three of the five spectral indices computed in the study (NDMI, GNDVI and SWIR_Stress) were considered as the foundation for developing the StressClass method. The methodological explanation for this selection is that the specified indices accurately represent the plant's water status, photosynthetic vitality and structural alterations in leaf tissue with maximal sensitivity, respectively. The StressClass categorization does not include of the NDWI and LSWI indices, although their usage in evaluating the irrigation regime and total moisture dynamics. The NDWI index's significant reliance on vegetation density and variations in spectral reflectance constrains its efficacy as a direct and consistent measure of plant stress. Therefore, to enhance its precision, specific indicators that directly correlate with the internal physiological stress and water deficiency of the cotton plant were added.

**Table 2. Sentinel-2 spectral band characteristics.**

| Band | Description | Central wavelength | Spatial resolution |
|---|---|---|---|
| B3 | Green | 560 nm | 10 m |
| B8 | NIR (Near Infrared) | 842 nm | 10 m |
| B11 | SWIR 1 (Short Wave IR) | 1610 nm | 20 m |
| B12 | SWIR 2 (Short Wave IR) | 2190 nm | 20 m |

***Source:*** The table was prepared by the author based on Sentinel-2 mission technical specifications.

The stress class thresholds were refined using index indicators confirmed in scientific literature [5], [8] real plant development in the study area. Each point (pixel) is separated into four primary categories by the classification algorithm, which is based on the following criteria:

- Images of healthy vegetation include pixels with low levels of structural stress, high levels of photosynthetic activity (GNDVI) and ideal leaf moisture (NDMI).
- Water stress arises when plant photosynthetic potential (green mass) is preserved while spectral moisture indicators drop sharply.
- Nutrient (nitrogen) stress weakens chlorophyll concentration and vegetative development despite adequate water supply.
- The most critical situations are complex stress, which causes moisture deprivation, physiological weakness and structural alterations in plant tissue.

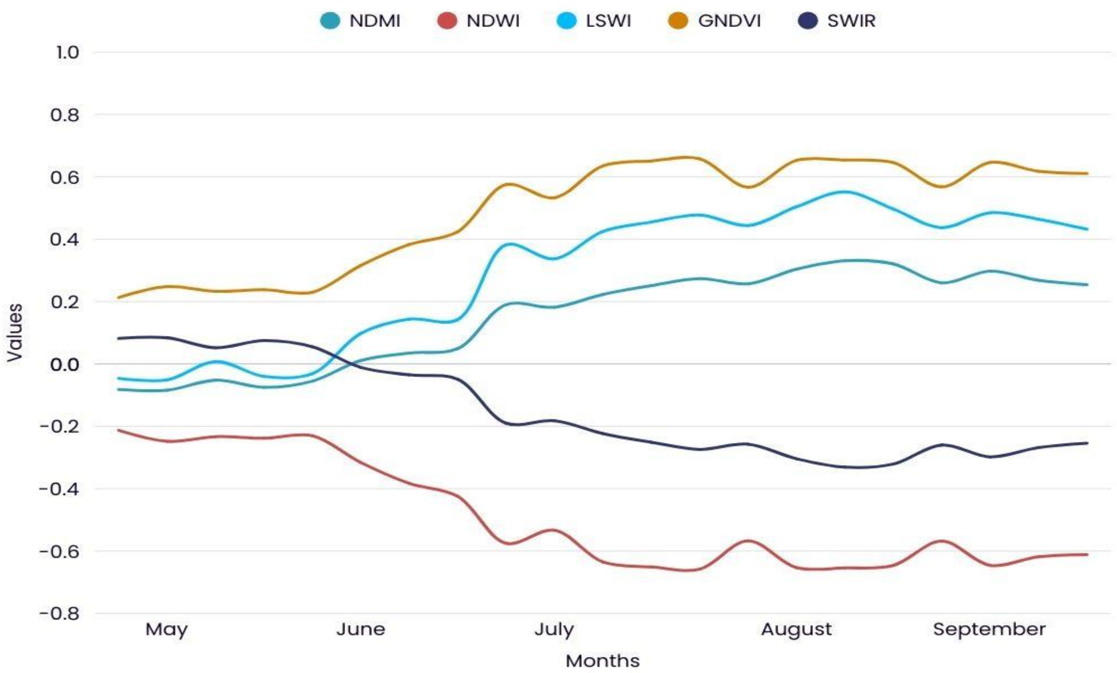
The study's spectral computations and time series analysis were executed on Google Earth Engine (GEE). GEE was applied to analyze pre-vectorized pivot contours as regions of interest. Calculated mean values of index indicators for each time period were added into the statistical dataset to track index changes during cotton vegetation.

## Result and discussion

### Time series analysis of spectral indices and phenological dynamics

Sentinel-2 data was assessed for the 2025 vegetation period in 6 pivot irrigation locations in Imishli district, encompassing 293.6 ha. The dynamics of 5 spectral indices in Figure 2 show the plant's spectral signature and phenological shifts from May to September. In the early monitoring period, low and steady indices are due to small cotton seedlings and soil background spectral reflectance dominating pixels. As the cotton plant grows its root system, aboveground biomass growth is limited. From mid-June forward, as cotton enters the rapid vegetative growth phase and the field is completely closed (canopy closure), spectral responses sharply differentiated and increased vertically.

**Figure 2. Comparative temporal series of vegetation indices throughout the cotton vegetation period.**




***Source:*** The chart was prepared by the author.

The GNDVI index improved the accuracy of monitoring cotton chlorophyll concentration because it is sensitive to the green spectral channel. The rapid development that started in late June peaked at 0.76 in mid-August. This peak time signifies the phase when cotton demonstrates maximal photosynthetic activity and nitrogen absorption reaches its highest point. This indicator demonstrates both the plant's health status and the energy reserve it accumulates for the reproductive phase.

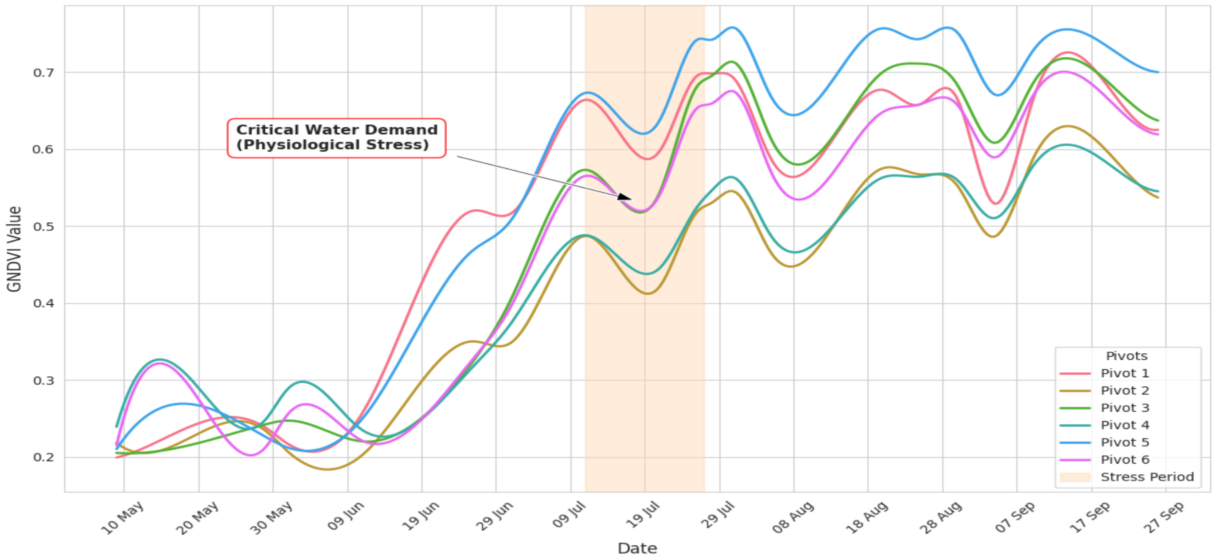
The water status of cotton was assessed through a simultaneous analysis of the NDMI and LSWI indices. Although both indices show the highest moisture content in August, a temporary decrease recorded in mid-July (during the critical flowering and boll formation stages) demonstrates the sensitivity of the plant to physiological water stress. The consistent decrease in SWIR values during this period confirms the increase in spectral absorption of water in plant tissues and the fact that the field is structurally completely represented by cotton cover.

The constant negative NDWI index during the vegetative period, peaking in its lowest point in August, signifies the absence of open water in the region and the attainment of maximum green biomass density. The minor spectrum changes noted at the end of September are attributable to the plant concluding its reproductive phase and beginning the natural senescence and maturation period. The reductions in GNDVI resulting from chlorophyll degradation during this period indicate the physiological processes subsequent to yield formation

**Inter-pivotal variation and spectral stability in cotton plant growth dynamics**

Figure 3 illustrates the GNDVI trajectories of 6 distinct pivots situated in the Imishli region. This differential analysis clarifies the spectral responses of individual plots to the irrigation scheme and regional climatic dynamics. From May until the conclusion of June, all pivots progressed along a nearly identical trajectory. The diminished GNDVI values (<0.3) during this period are attributable to the impact of the soil backdrop. The strong synchronization among plots demonstrates that resources (water and fertilizer) were uniformly allocated across the region during the first development phase.

**Figure 3. Temporal Dynamics of GNDVI Across Six Distinct Pivots.**




***Source:*** The chart was prepared by the author.

The study indicates that from July 9 to 26, a significant fall or peak is evident in the GNDVI values across all pivots. The determination of the "Critical Water Demand" phase for cotton is substantiated by two primary factors: The significant decrease in the indices is a global indicator of a deceleration in plant growth. The uniformity among pivots is maximal at this point. In agronomic terms, July marks the flowering and boll development phase of cotton. As the transpiration rate peaks during this period, insufficient irrigation leads to physiological stress in the plant, which is promptly evident in the spectrum response of the GNDVI measurements.

The transition of cotton from the peak reproductive stage to the generative stage is related to the slight spectral changes that were noticed in the month of August and the beginning of September. These changes do not have a significant impact on the final yield in comparison to the key stress period that occurs in July. This is due to the fact that the primary structural components of the crop, known as the bolls, have already been produced at this time. It is confirmed that the functionality of the plant's green mass has been preserved by the fact that the GNDVI is an ideal indication for monitoring nitrogen and water stress throughout this period.

Beginning around the middle of September, spectral distinctions between pivots gradually become apparent. Both Pivot 5 and Pivot 3 continue to have high values during this process, which is represented as "Pre-harvest differences" in Figure 3. On the other hand, Pivot 2 and Pivot 4 observe a decline. It is reasonable to explain this situation by referring to the natural aging period of cotton, the heterogeneity of the soil, or the defoliation measures that are implemented at different occasions throughout fields.

The coefficient of variation (CV) for the six separate pivots was a mere 4.2% during the peak vegetation period. This minimal value verifies that the implemented center pivot irrigation system is very steady over an area of 293.6 hectares. This statistical outcome scientifically guarantees the efficacy of irrigation and the uniform allocation of resources across the area.

**Stress map interpretation**

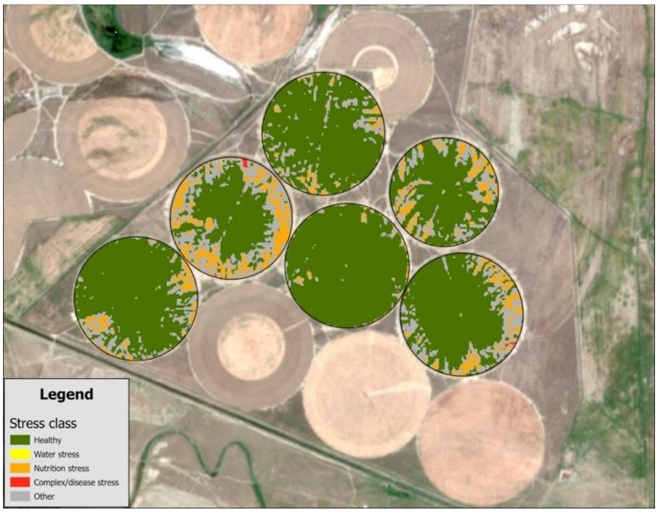
The stress condition of cotton fields was assessed using the average spectral values of each 10-meter pixel during the peak vegetation phase (late July to early August). Only NDMI, GNDVI and SWIR-based indices were used in the StressClass classification (Figure 4). A Sentinel-2 image from July 28, 2025 has been used as an overlay for enhanced visual comprehension. The primary rationale for this selection is that the physical interpretation of the NDWI index is not consistent completely with the assessment of internal plant stress. NDWI primarily responds to open water surfaces and soil moisture, although becomes excessively reliant on variations in spectral reflectance when vegetation density escalates. This constrains its capacity to function as a reliable indication of internal plant physiological stress. Conversely, NDMI directly indicates plant water status, GNDVI represents photosynthetic activity and SWIR reveals structural alterations at the cellular level, hence enhancing the precision of the methodology ***(table 3)***.

**Table 3. Stress classification of cotton fields based on spectral indicators.**

| StressClass | Area (ha) | Percent (%) | Classification Criteria |
|---|---|---|---|
| **Healthy** | 217.7 | 72.74 | High GNDVI (>0.50) and Positive NDMI |
| **Water stress** | 0.1 | 0.03 | Negative NDMI and High SWIR_Stress |
| **Nitrogen stress** | 23.4 | 7.82 | Low GNDVI (<0.45) and Normal NDMI |
| **Disease** | 0.3 | 0.10 | Negative slope of all indices |
| **Other** | 57.8 | 19.31 | Non-vegetative spectral signal |

***Source:*** Own computation

**Figure 4. Stress class map for cotton grown on pivot irrigation systems.**




***Source:*** The map was prepared by the author using spatial analysis and remote sensing techniques.

The mean values of the indices were used as the foundation to guarantee the accuracy of the classification. This method facilitated a detailed evaluation of micro-changes within the domain and localized stress concentrations. The analysis of the stress map indicates that the middle regions of the pivot areas are entirely within the Healthy zone, with a ratio of 72.74%. The map analysis indicates that the predominant portion of the research area belongs inside the Healthy vegetation category. These zones mostly encompass the basis and interior regions of the pivot areas. The spectral profile of the healthy areas is marked by consistently elevated GNDVI (>0.50) and positive NDMI values, indicating that both the photosynthetic biomass and tissue hydration of the plant are at ideal levels. The existence of substantial healthy areas under the extreme heat of the Imishli region during July and August illustrates the effectiveness of the pivot irrigation system in efficiently and uniformly satisfying the water requirements of the plants.

Nitrogen stress" (7.82% of the total) has the highest concentration of the area's observed variances. Spatial study indicates that this form of stress is not systematic and mainly distributed in the outside zones of the pivots or in localized regions where the soil topography varies. The positive NDMI, combined with a relatively low GNDVI in these regions, indicates that the issue is not directly associated with water scarcity, but rather with the diversity of soil fertility or the uneven application of nitrogen fertilizer.

The "Water stress" category covers a minimal area of around 0.1 hectares (0.03%). This outcome indicates that none of the six analyzed pivots encountered significant moisture shortages during the growth season. Complex or disease-induced stress zones (0.3 ha) were identified outside the pivots, primarily on marginal lands excluded from crop rotation. This observation confirms the efficacy of the StressClass approach in identifying cotton from other cover kinds and in identifying certain stress types.

The findings differ from and are comparable to research on spectral monitoring of cotton plants published in international journals. Recent research on cotton plant monitoring indicate that the combination of SWIR and Green spectral channels yields the greatest accuracy in assessing leaf water content and nitrogen concentration [14]. The identical results of the NDMI and LSWI indices used to conduct our research are attributed to their collective sensitivity to vegetation water content and soil moisture. The NDWI index is excluded because it reacts promptly to irrigation events and is sensitive to variations in plant moisture solely in the upper layer [2], [15]. This method scientifically provides a more consistent assessment of physiological stress in cotton.

Recent research on central pivot systems pointed out the efficacy of integrating sensor packages directly connected to pivot devices for the detection of water stress [16]. This investigation suggests that, as an alternative to costly approaches necessitating specialized hardware, regional monitoring of pivot fields may be conducted with comparable efficiency with Sentinel-2 satellite data and the 'StressClass' algorithm. The effective reproduction of high-resolution data from in-field sensors by Sentinel-2 NDMI and SWIR indices validates that suggested approach is more accessible and cost-efficient for large-scale agricultural management. In the face of regional climatic anomalies like rising temperatures and diminishing precipitation, operational monitoring systems are essential for cotton growing.

The synthesis of the implemented studies indicates that the combination of multispectral satellite data with machine learning algorithms is crucial for modeling physiological markers of cotton plants, including biomass, nitrogen absorption and stem water potential (SWP) [2], [17]. This integration creates extensive prospects for the development of large-scale, high-precision monitoring platforms in agriculture. The GNDVI index's indication of water deficit effects on plant health and photosynthetic activity rather than direct water stress aligns with international research findings [18]. Research has indicate incorporating Red Edge and SWIR spectral regions into the analytical procedure markedly enhances forecast accuracy. The SWIR-based StressClass method showed significant sensitivity to water deficiency in cotton tissue, enabling the detection of structural stress prior to the appearance of visual signs [6], [19]. The integration of data from several sensors enhances the efficacy of the methods employed in the differential management of water and nutrient resources.

## Conclusion

A study in the pivot irrigation zones in the Imishli region showed that Sentinel-2 multispectral satellite data had significant predictive capability for monitoring moisture and stress dynamics in cotton crops. The integrated use of NDMI, LSWI and GNDVI indices facilitates the concurrent evaluation of biomass vitality and tissue hydration in cotton. The research indicates that concentration primarily on photosynthetic activity (GNDVI) in cotton field monitoring is insufficient for a comprehensive evaluation of plant health. The incorporation of indices derived from water-sensitive spectral channels (SWIR) is essential for developing an early warning system in irrigation management. This method enables precise detection of water deficiency in plant tissues prior to the visible onset of stress symptoms.

Time series analysis pointed out water stress detected during the pivotal phenological stage of cotton, accompanied by precise statistical signals. The temporary decrease in GNDVI values seen in mid-July highlighted the disparity between the plant's transpiration requirements and water availability, acting as a definitive metric for the operational modification of irrigation rates. Differential analysis validated a significant level of temporal synchronization among the six individual pivots. The coefficient of variation at the peak of vegetation is below 5%, scientifically ensuring that the central pivot system delivers consistent and uniform moisture distribution throughout an extensive area. The spectral difference noted at the season's conclusion is associated with pre-harvest management and soil variability and it does not undermine the overall irrigation efficiency.

The StressClass maps that were generated make it possible to identify zones of local moisture deficit as well as within-field heterogeneity at the pixel level. The proposed method combines conventional subjective observations with quantitative metrics derived from Sentinel-2 satellite data, providing the monitoring process entirely automated and continuous. This methodology develops a robust scientific foundation for the differentiated management of resources, including water, energy and labor, which is particularly crucial for dry areas such as Imishli.

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**Peyk təsvirlərindən istifadə etməklə pivot suvarma zonalarında pambığın inkişafının qiymətləndirilməsi və təhlili**


***Xülasə***

*Suvarma idarəçiliyi və su resurslarının səmərəli istifadəsi kənd təsərrüfatında məhsuldarlığın artırılması və ətraf mühitin qorunması üçün kritik əhəmiyyət daşıyır. Xüsusilə pivot suvarma sistemləri ilə becərilən pambıq sahələrində suyun qeyri-bərabər paylanması və bitkilərin su stressi məhsuldarlığa birbaşa təsir göstərir. Bu baxımdan, su rejiminin və vegetasiya vəziyyətinin operativ və etibarlı monitorinqi kənd təsərrüfatı qərarlarının optimallaşdırılması üçün vacibdir. Aparılan tədqiqat Sentinel-2 multispektral peyk məlumatları və suya həssas spektral indekslərin birgə istifadəsinin pivot sahələrində su rejimi, rütubət dinamikası və stress proseslərini* *izləməkdə yüksək effektivliyini göstərmişdir. NDMI, NDWI və LSWI indeksləri suvarma dövrlərinin və torpaq-bitki su balansının qiymətləndirilməsində əsas göstərici rolunu oynayır, GNDVI və SWIR əsaslı indekslər isə vegetasiya reaksiyalarını və su stressini erkən mərhələdə aşkarlamağa imkan verir. Stress xəritələri göstərmişdir ki, pivot sahələrinin əksəriyyəti sağlam vegetasiya vəziyyətindədir, su stressi minimaldır və sistematik xarakter daşımır, müşahidə olunan əsas risk faktoru isə idarəolunan qida stressidir. Bu yanaşma su stressinin erkən aşkarlanması və rütubət idarəçiliyinin optimallaşdırılması üçün güclü elmi-praktik əsas yaradır.*

**Açar sözlər:** *pivot, pambıq, vegetasiya indeksi, peyk təsvirləri, su stressi.*

Б.Х. Бабашлы

Национальная Авиационная Академия

## Использование спутниковых снимков для оценки и анализа роста хлопчатника в зонах кругового орошения

*Резюме*

*Управление орошением и рациональное использование водных ресурсов имеют решающее значение для повышения сельскохозяйственной продуктивности и защиты окружающей среды. В частности, на хлопковых полях, орошаемых системами кругового орошения, продуктивность в значительной степени зависит от неравномерного распределения воды и водного стресса растений. В связи с этим оптимальное использование сельскохозяйственных ресурсов требует постоянного и эффективного мониторинга состояния растительности и водного режима. Исследование показало, что использование водочувствительных спектральных индексов и мультиспектральных данных Sentinel-2 является высокоэффективным для мониторинга водного режима, динамики влажности и стрессовых процессов на полях с круговым орошением. Для оценки циклов орошения и почвенно-растительного водного баланса индексы NDMI, NDWI и LSWI имеют решающее значение, в то время как индексы на основе GNDVI и SWIR позволяют выявлять реакцию растительности и водный стресс на ранней стадии. Полученные карты стресса свидетельствуют о том, что большинство полей с круговым орошением находятся в хорошем состоянии, уровень водного стресса невелик и не систематичен, а основным фактором риска является контролируемый дефицит питательных веществ. Предложенный подход формирует научно-практическую основу для раннего выявления водного стресса и оптимизации управления водным режимом сельскохозяйственных угодий.*

**Ключевые слова:** *поворотное орошение, хлопок, индекс растительности, спутниковые снимки, водный стресс.*