

SATELLITE-POWERED IRRIGATION INTELLIGENCE: A DECISION-SUPPORT SYSTEM FOR RESILIENT AGRICULTURE

INTELLIGENCE SATELLITAIRE AU SERVICE DE L'IRRIGATION: UN SYSTÈME D'AIDE À LA DÉCISION POUR UNE AGRICULTURE RÉSILIENTE

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ABSTRACT

Climate change is increasing drought risk and water-management pressure in agricultural systems, creating a need for practical tools that support strategic irrigation planning rather than only short-term drought response. This paper presents a satellite-based decision-support system for mapping irrigation suitability in agricultural areas of eastern Croatia. The system was developed as a proof of concept to identify areas where irrigation investments are technically feasible, economically justified and likely to contribute to long-term agricultural resilience.

The methodology integrates Sentinel-2 imagery, terrain data, soil properties, crop-specific parameters and infrastructure information within a Multi-Criteria Analysis framework. Five criteria were used: infrastructure proximity, soil irrigation suitability, slope suitability, Management Allowable Depletion and Vegetation Stress Index. The criteria were normalized to a common suitability scale and weighted using the Analytic Hierarchy Process. The final output is a spatially continuous Irrigation Suitability Map, classified into suitability categories and delivered through a WebGIS platform for visualization, comparison and interpretation by agricultural stakeholders and public authorities.

The analysis covered approximately 150 km² of agricultural land, while validation and interpretation were supported by in situ soil water content measurements collected by FAZOS within a 250 ha test site during the 2025 growing season. Measurements were available for three representative soil types and multiple depths within the active root zone. The comparison showed that soil water content and irrigation suitability describe complementary processes. Soil water content reflects short-term climatic and field conditions, while the suitability map identifies long-term structural potential for irrigation development. The results demonstrate that areas with low soil water content and high irrigation suitability can be considered priority zones for strategic irrigation development. Conversely, areas with low soil water content but low suitability indicate locations where irrigation may be technically difficult, costly or less sustainable. By explicitly distinguishing irrigation need from irrigation suitability, the proposed system supports evidence-based planning and more sustainable allocation of limited water resources.

Keywords: Irrigation suitability, Sentinel-2, multi-criteria analysis, WebGIS, soil water content, resilient agriculture.

RÉSUMÉ

Le changement climatique accroît le risque de sécheresse et la pression sur la gestion de l'eau dans les systèmes agricoles, ce qui crée un besoin d'outils pratiques favorisant une planification stratégique de l'irrigation plutôt qu'une simple réponse à court terme à la sécheresse. Cet article présente un système d'aide à la décision fondé sur les données satellitaires pour cartographier l'aptitude à l'irrigation dans les zones agricoles de l'est de la Croatie. Le système a été développé comme preuve

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de concept afin de repérer les zones où les investissements dans l'irrigation sont techniquement réalisables, économiquement justifiés et susceptibles de contribuer à la résilience agricole à long terme.

La méthodologie intègre des images Sentinel-2, des données topographiques, les propriétés des sols, des paramètres propres aux cultures et des informations sur les infrastructures dans un cadre d'analyse multicritère. Cinq critères ont été utilisés : la proximité des infrastructures, l'aptitude des sols à l'irrigation, l'aptitude liée à la pente, le déficit hydrique maximal admissible et l'indice de stress de la végétation. Les critères ont été normalisés sur une échelle commune d'aptitude et pondérés au moyen du processus d'analyse hiérarchique. Le résultat final est une carte spatialement continue de l'aptitude à l'irrigation, répartie en catégories d'aptitude et mise à disposition sur une plateforme WebGIS afin que les acteurs agricoles et les autorités publiques puissent la visualiser, la comparer et l'interpréter.

L'analyse a porté sur environ 150 km² de terres agricoles. Sa validation et son interprétation ont été étayées par des mesures in situ de la teneur en eau du sol, recueillies par FAZOS sur un site d'essai de 250 ha pendant la campagne agricole de 2025. Les mesures étaient disponibles pour trois types de sols représentatifs et à plusieurs profondeurs dans la zone racinaire active. La comparaison a montré que la teneur en eau du sol et l'aptitude à l'irrigation décrivent des processus complémentaires. La teneur en eau du sol reflète les conditions climatiques et parcellaires à court terme, tandis que la carte d'aptitude permet de déterminer le potentiel structurel à long terme pour le développement de l'irrigation.

Les résultats montrent que les zones présentant une faible teneur en eau du sol et une forte aptitude à l'irrigation peuvent être considérées comme prioritaires pour le développement stratégique de l'irrigation. À l'inverse, une faible teneur en eau du sol associée à une faible aptitude signale des zones où l'irrigation pourrait être techniquement difficile, coûteuse ou moins durable. En distinguant explicitement le besoin d'irrigation de l'aptitude à l'irrigation, le système proposé favorise une planification fondée sur des données probantes et une répartition plus durable des ressources en eau limitées.

Mots clés : Aptitude à l'irrigation; Sentinel-2; Analyse multicritère; WebGIS; Teneur en eau du sol; Agriculture résiliente,

INTRODUCTION

Agricultural production systems are increasingly exposed to climate-related risks, including prolonged drought periods, irregular precipitation patterns, and growing competition for water resources. These pressures are particularly relevant in regions where agricultural productivity depends on the ability to adapt water management practices to changing environmental conditions. Irrigation is often considered a direct response to water scarcity, but its long-term contribution to agricultural resilience depends on where, how, and under which physical, agronomic, and infrastructural conditions it is implemented. In Croatia, irrigation remains relatively underdeveloped compared with the country's agricultural potential and available water resources. This creates a need for data-driven approaches that can support the identification of areas where irrigation development would provide the greatest benefit. Traditional irrigation planning is often constrained by fragmented spatial information, limited field-level monitoring, and insufficient integration of soil, crop, terrain, infrastructure, and climatic indicators. As a result, decisions on irrigation investments may not always reflect the combined technical and environmental conditions that determine long-term feasibility. Earth Observation data provide an opportunity to improve irrigation planning by enabling repeated, spatially continuous monitoring of agricultural areas. Sentinel-2 satellite imagery is particularly useful for agricultural applications due to its spatial resolution, temporal revisit frequency, and spectral bands suitable for vegetation monitoring. However, satellite-derived indicators alone cannot fully determine irrigation suitability. Vegetation condition may reflect short-term stress, crop phenology, or management differences, while irrigation feasibility also depends on terrain characteristics, soil properties, infrastructure accessibility, and crop-specific water management parameters. For this reason, irrigation

suitability assessment requires a multi-criteria approach. Multi-Criteria Analysis allows heterogeneous datasets to be normalized, weighted, and combined into a single spatial index. When combined with the Analytic Hierarchy Process, expert knowledge can be incorporated into the weighting of criteria according to their relative importance for irrigation planning. Such an approach is particularly suitable for strategic decision-making because it distinguishes between immediate water stress and the structural potential for effective irrigation development.

This paper presents a proof-of-concept decision-support system for satellite-based irrigation suitability assessment in agricultural areas of eastern Croatia. The system integrates Sentinel-2 imagery, terrain data, soil information, infrastructure proximity, crop-specific Management Allowable Depletion, and in situ soil water content measurements. The final output is delivered through a WebGIS platform designed to support visualization, comparison, and interpretation of irrigation suitability maps and related criteria layers. The objective of the paper is threefold. First, it describes the methodology used to generate irrigation suitability maps through a multi-criteria framework. Second, it presents the system architecture developed to separate offline analytical processing from user-oriented WebGIS visualization. Third, it discusses the validation and interpretation of results using soil water content measurements collected during an exceptionally dry growing season. By explicitly distinguishing irrigation suitability from immediate irrigation need, the proposed system supports more sustainable allocation of limited water resources and contributes to climate-resilient agricultural planning.

STUDY AREA AND DATA

The study was conducted in eastern Croatia, within the Slavonia and Baranja agricultural region. The area was selected due to its high agricultural importance, large field structures suitable for satellite-based monitoring, variable soil-water dynamics, and increasing exposure to drought-related production risks. The analysed area covers approximately 150 km² of agricultural land, while detailed field validation was carried out within a 250 ha test site where in situ soil water content measurements were available. The location of the area of interest is shown in Figure 1.



Figure 1. Location of the area of interest in eastern Croatia used for satellite-based irrigation suitability assessment

The region is representative of agricultural landscapes where irrigation planning requires the integration of physical, agronomic, and infrastructural information. Although Croatia has significant water resources, irrigation remains underdeveloped, and agricultural production is increasingly affected by climate variability. The selected study area therefore provides a relevant test case for developing and validating a decision-support approach aimed at identifying areas where irrigation investments would be most effective and sustainable. The analysis was based on the integration of

Earth Observation data, geospatial reference layers, crop-related parameters, and field measurements. Sentinel-2 Level-2A imagery was used as the primary Earth Observation input. The satellite data were processed for the main agricultural growing season and used to derive vegetation-related indicators, including the Vegetation Stress Index. Terrain information was derived from the EU-DEM dataset and used to calculate slope suitability. Soil irrigation suitability was based on pedological information describing soil properties relevant to water retention and infiltration.

Infrastructure proximity was calculated from available spatial data representing existing water-related infrastructure, including canals, pipelines, and pumping stations where available. Crop-specific Management Allowable Depletion values were used to represent the tolerance of selected crops to soil moisture depletion. The irrigation suitability assessment combined five criteria: infrastructure proximity, soil irrigation suitability, terrain slope, Management Allowable Depletion, and Vegetation Stress Index. These criteria were selected to represent the main structural, environmental, and agronomic factors influencing the feasibility and potential effectiveness of irrigation. Each criterion was prepared as a spatial layer and normalized to a common suitability scale before integration in the multi-criteria framework. In situ soil water content measurements, collected by FAZOS during the 2025 growing season, were used for validation and interpretation of the model outputs. Measurements were collected during the 2025 growing season on three representative soil types: Chernozem on loess, humofluvisol chernozemic, and shallow gleyed humofluvisol. Soil water content was measured at multiple depths, including 10, 20, 30, and 40 cm, allowing the assessment of moisture dynamics within the active root zone. The 2025 season was characterized by exceptionally dry conditions, which provided a useful stress scenario for evaluating the relationship between structural irrigation suitability and observed soil moisture conditions. The soil water content dataset was not used as a direct input into the MCA model. Instead, it was used as an independent validation and interpretation dataset. This distinction is important because the MCA-based irrigation suitability map represents long-term structural potential for irrigation development, while soil water content measurements reflect short-term hydrological and climatic conditions at specific locations and dates.

METHODOLOGY

The methodology was designed to assess irrigation suitability as a structural and strategic property of agricultural land, rather than as a direct indicator of immediate water deficit. The approach combines Earth Observation data, ancillary geospatial datasets, crop-specific parameters, and expert-based weighting within a Multi-Criteria Analysis framework. The overall workflow is shown in Figure 2.



Figure 2. Processing and user-interaction workflow for the satellite-based irrigation suitability decision-support system

Sentinel-2 Level-2A imagery was used as the main satellite data source. The imagery was acquired for the agricultural growing seasons covered by the analysis and processed through an offline workflow including data download, cloud masking, resampling, and calculation of vegetation-related indicators. The Vegetation Stress Index was derived from Sentinel-2 vegetation information and used as a criterion representing crop condition and temporal stability. The use of satellite time series enabled the production of irrigation suitability outputs for individual acquisition dates as well as seasonal aggregated products.

The Multi-Criteria Analysis included five evaluation criteria: infrastructure proximity, soil irrigation suitability, terrain slope suitability, Management Allowable Depletion, and Vegetation Stress Index. Infrastructure proximity was used as an indicator of technical feasibility and implementation cost, assuming that agricultural fields closer to existing water infrastructure are more suitable for irrigation development. Soil irrigation suitability represented pedological properties relevant to water retention, infiltration, and irrigation response. Terrain slope was derived from the EU-DEM dataset, with flatter areas considered more favourable for irrigation system installation and operation. Management Allowable Depletion represented crop-specific tolerance to soil moisture depletion, while the Vegetation Stress Index provided satellite-derived information on vegetation condition.

Before aggregation, each criterion was normalized to a common suitability scale ranging from 0 to 1. This step allowed heterogeneous datasets with different units, spatial properties, and value ranges to be compared and integrated. Higher values represented more favourable conditions for irrigation suitability. The final irrigation suitability score was calculated using a weighted linear combination:

$$S = \sum w_i x_i$$

where S is the final irrigation suitability score, w_i is the weight assigned to criterion i , and x_i is the normalized value of criterion i . The resulting score was classified into qualitative suitability categories to support interpretation in the WebGIS environment.

The relative importance of the criteria was defined using the Analytic Hierarchy Process. The weighting scheme reflects the objective of identifying areas where irrigation would be technically feasible, economically justified, and operationally sustainable. Infrastructure proximity received the highest weight, followed by soil suitability and slope suitability, while Management Allowable Depletion and Vegetation Stress Index acted as supporting agronomic and temporal criteria.

Table 1. Criteria weights used in the AHP-based irrigation suitability model

	Criterion	Weight
1	Infrastructure Proximity	0.39
2	Soil Suitability	0.26
3	Slope Suitability	0.17
4	Management Allowed Depletion	0.11
5	Vegetation Stress Index	0.07

Crop-specific Management Allowable Depletion values were used to account for differences in crop tolerance to soil moisture depletion. The values were assigned to the main crop types represented within the study area and used as an input criterion in the MCA framework.

Table 2. Crop-specific Management Allowable Depletion values used in the analysis

Crop	MAD (%)
Maize	60-70
Wheat	30-40
Sunflower	45-50
Soybean	60-70

Crop classification was implemented as a supporting component of the system. A supervised machine learning approach based on gradient-boosted decision trees was used to classify major crop types

from Sentinel-2 spectral time series. The crop classification outputs were used as contextual layers for interpretation and for assigning crop-specific parameters such as Management Allowable Depletion. The crop classification component was not the primary output of the system, but it supported the interpretation of suitability results in relation to crop-specific water management characteristics. The final MCA outputs were generated as GeoTIFF raster layers representing spatially continuous irrigation suitability across the study area. Outputs were produced for the main growing season and for selected individual satellite acquisition dates, enabling both seasonal interpretation and temporal comparison. The resulting layers were validated and prepared for publication through the WebGIS platform.

SYSTEM IMPLEMENTATION AND WEBGIS VISUALIZATION

The proof-of-concept system was implemented using a modular workflow that separates offline analytical processing from WebGIS-based visualization. This design ensures that all satellite processing, data preparation, model execution, and validation are completed in a controlled analytical environment before results are published to end users.

In the offline processing stage, Sentinel-2 imagery and ancillary geospatial datasets are acquired, preprocessed, and transformed into spatial indicators used in the irrigation suitability assessment. This includes cloud masking and resampling of satellite imagery, calculation of vegetation-related indices, preparation of terrain and soil criteria, crop classification, and execution of the MCA model. The outputs of this stage are validated raster layers, primarily in GeoTIFF format, representing irrigation suitability and individual criteria layers.

The WebGIS application serves as the dissemination and interpretation component of the system. It does not perform real-time image processing or on-demand modelling. Instead, it provides access to pre-computed and validated outputs generated during the offline processing stage. This approach improves system stability and ensures that users interact only with verified results.

The user interface allows users to visualize irrigation suitability maps, inspect individual MCA criteria layers, and select outputs for different years or satellite acquisition dates. The layer panel provides access to slope suitability, vegetation stress, soil irrigation suitability, infrastructure proximity, Management Allowable Depletion, crop classification, and final irrigation suitability outputs. Users can also compare two selected temporal layers using a split-screen comparison tool, supporting the interpretation of seasonal changes in vegetation condition and irrigation suitability.

Additional map tools include distance and area measurement functions, which support basic spatial interpretation directly within the application. The system is accessible through a standard web browser and was designed to remain usable on both desktop and mobile devices. An example of the WebGIS interface displaying the seasonal irrigation suitability output is shown in

Figure 3.



Figure 3. WebGIS interface displaying the seasonal irrigation suitability map and classification legend for the study area

The system was developed as a Technology Readiness Level 3 proof of concept. Therefore, its purpose is to demonstrate the feasibility of the methodology and the usability of the visualization platform, rather than to provide a fully operational real-time irrigation scheduling service. Future development will focus on automation of data ingestion, integration of dynamic climatic variables, user-defined areas of interest, and broader deployment for operational irrigation planning.

RESULTS AND VALIDATION

The developed methodology produced spatially continuous irrigation suitability maps for the agricultural area of interest covering approximately 150 km². The outputs were generated as raster layers representing the final suitability score and the individual MCA criteria used in the assessment. The final irrigation suitability map classifies agricultural land into suitability categories ranging from unsuitable to very high suitability, enabling interpretation by both technical users and agricultural stakeholders.

The spatial distribution of irrigation suitability showed clear and interpretable patterns. Areas classified as highly suitable were generally associated with flat terrain, favourable soil properties, and proximity to existing water-related infrastructure. These locations represent zones where irrigation development would likely require lower implementation effort and where added water could provide higher agronomic benefit. Lower suitability areas were typically linked to less favourable terrain, poorer soil conditions, or greater distance from infrastructure, indicating locations where irrigation would be technically more challenging or economically less efficient.

In addition to the final suitability map, the system generated individual criteria layers, including slope suitability, soil irrigation suitability, infrastructure proximity, Management Allowable Depletion, Vegetation Stress Index, and crop classification. These layers allow users to interpret the contribution of each factor to the final result and to distinguish between structural constraints and crop-related or vegetation-related conditions. This is important because the same final suitability class can result from different combinations of limiting factors.

The WebGIS platform enabled the dissemination and interpretation of the generated outputs. Users can visualize seasonal irrigation suitability maps, inspect individual criteria layers, and compare outputs from different dates or years. The temporal comparison tool supports the visual assessment of changes in vegetation condition and suitability patterns across the growing season. This functionality is particularly useful for identifying areas where seasonal vegetation stress develops repeatedly and where irrigation planning may require closer attention.

System verification was performed through a structured set of test cases covering architecture, visualization, interaction tools, temporal comparison, base map functionality, mobile usability, and consistency with validation data. All test cases were successfully completed. The WebGIS application correctly displayed the predefined pilot area, rendered irrigation suitability and MCA criteria layers, enabled temporal comparison, and provided functional distance and area measurement tools. The application also remained usable across desktop and mobile devices, confirming the suitability of the interface for broader stakeholder interaction.

Validation of the irrigation suitability outputs was performed using in situ soil water content measurements collected during the 2025 growing season. Measurements were available for three representative soil types and were collected at multiple depths, including 10, 20, 30, and 40 cm. The 2025 season was characterized by exceptionally dry conditions, which provided a relevant stress scenario for evaluating the relationship between structural irrigation suitability and observed soil moisture dynamics.

The comparison between irrigation suitability outputs and soil water content measurements confirmed that the two datasets represent related but distinct aspects of agricultural water management. Soil water content reflects short-term hydrological conditions influenced by recent precipitation, evapotranspiration, soil texture, crop development stage, and local field conditions. In contrast, the

MCA-based irrigation suitability map represents long-term structural potential for irrigation development, integrating infrastructure proximity, soil suitability, terrain slope, crop-specific depletion tolerance, and vegetation stress information.

During the dry 2025 season, low soil water content values were observed across different parts of the study area, including areas classified as both high and low irrigation suitability. This result does not indicate inconsistency in the model. Instead, it confirms that irrigation need and irrigation suitability should not be interpreted as identical concepts. Areas with low soil water content and high irrigation suitability can be considered priority zones for strategic irrigation development, because they combine current water stress with favourable structural conditions for effective irrigation. Conversely, areas with low soil water content but low suitability indicate locations where irrigation may be needed from a water-stress perspective but may be difficult, costly, or less sustainable to implement.

The validation therefore supports the interpretation of the MCA output as a planning-oriented suitability layer rather than a real-time drought or soil moisture product. The soil water content dataset provides complementary information that helps distinguish where water stress is occurring from where irrigation development is likely to be feasible and beneficial. This distinction is central to the decision-support value of the system, as it helps avoid the assumption that all drought-affected areas are equally suitable for irrigation investment.

Overall, the results demonstrate that the integration of Sentinel-2 data, geospatial criteria, crop-specific parameters, and WebGIS visualization can support evidence-based irrigation planning. The system provides a practical framework for identifying priority zones for irrigation development, interpreting spatial drivers of suitability, and supporting agricultural resilience under increasing climatic constraints.

CONCLUSIONS AND FUTURE WORK

This paper presented a satellite-based decision-support system for irrigation suitability assessment in agricultural areas of eastern Croatia. The system integrates Sentinel-2 imagery, terrain data, soil information, infrastructure proximity, crop-specific Management Allowable Depletion, and vegetation stress indicators within a Multi-Criteria Analysis framework. The criteria were weighted using the Analytic Hierarchy Process and combined into spatially continuous irrigation suitability maps covering approximately 150 km² of agricultural land.

The developed proof-of-concept system demonstrates that irrigation suitability can be assessed as a structural planning indicator rather than as a direct measure of current drought or soil moisture status. Validation using in situ soil water content measurements showed that soil moisture and irrigation suitability provide complementary information. Soil water content reflects short-term climatic and field conditions, while the suitability map identifies where irrigation development is technically feasible, economically justified, and likely to provide long-term benefit.

The WebGIS platform enables users to visualize final suitability maps, inspect individual criteria layers, compare temporal outputs, and perform basic spatial measurements. This makes the system useful not only as an analytical tool but also as a communication and planning platform for agricultural stakeholders and public authorities.

Future development should focus on increasing the operational maturity of the system. Key improvements include automated ingestion of new satellite data, integration of dynamic climatic indicators such as precipitation and evapotranspiration, expansion of validation datasets, and support for user-defined areas of interest. Further work should also include testing across larger agricultural regions and under different crop and soil conditions. These developments would support the transition from a proof-of-concept system towards an operational decision-support service for climate-resilient irrigation planning.

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