Colegio de Postgraduados

Development of a GeoJSON-Based Tool for the Integration and Visualization of Agronomic and Cartographic Data Applied to Agricultural Irrigation Management

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ABSTRACT

Objective: To develop a computational tool for the integration and visualization of agronomic and cartographic data in GeoJSON format, applied to agricultural irrigation management.

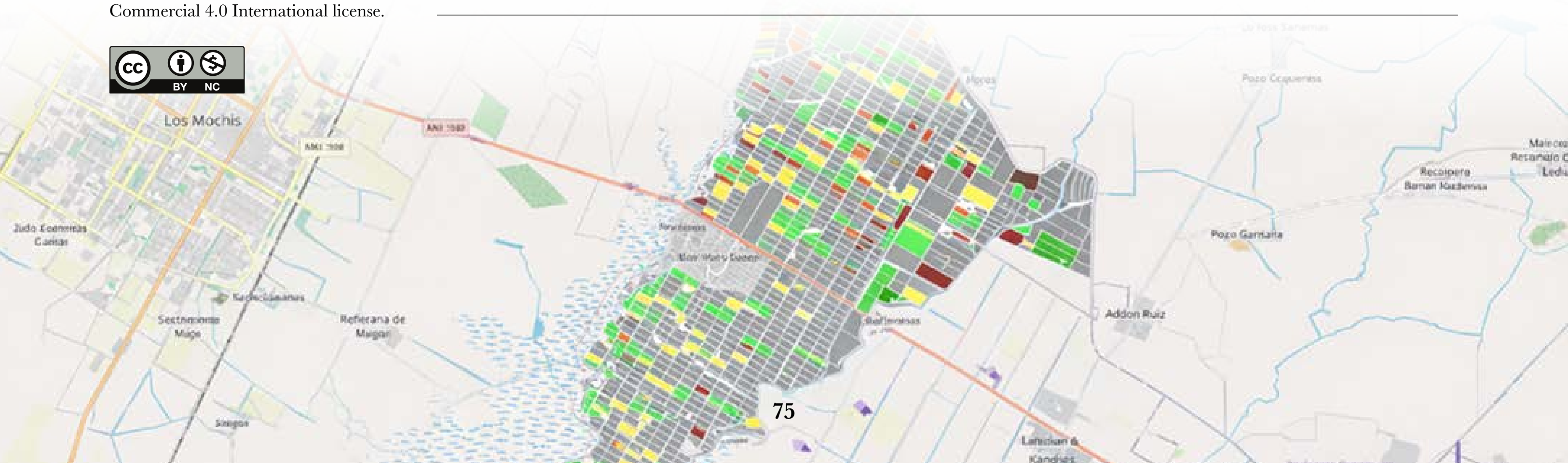
Design/methodology/approach: A descriptive and applied approach was adopted through the design of a Python-based system that links spatial information in shapefile format with tabular agronomic data derived from spreadsheets. The process incorporates identifier normalization, tabular-to-spatial joining, and automated export in compliance with the RFC 7946 standard. The tool was implemented using real data from the Batequis Irrigation Module of Irrigation District 075, located in northern Sinaloa, Mexico.

Results: The system generated an interoperable GeoJSON file that preserved the geometric integrity of agricultural plots and the consistency of agronomic attributes. Geospatial visualization enabled the interpretation of water stress distribution at the plot level. The usability evaluation yielded an average score of 82.5 on the System Usability Scale (SUS), while the functional evaluation, based on ISO/IEC 25010, showed a compliance level of 94%.

Limitations on study/implications: The tool was applied in a single irrigation module; therefore, its performance is associated with the operational and agronomic conditions of that specific context. Its application in other irrigation modules and districts is recommended in order to broaden the scope of the results.

Findings/conclusions: The developed tool provides a robust technical foundation for strengthening the digitalization of irrigation services through interoperable geospatial products. The proposed solution is both viable and pertinent for enhancing the integration, visualization, and analysis of agricultural information, thereby contributing to more informed decision-making in irrigation management.

Keywords: GeoJSON; irrigation management; geospatial integration.



INTRODUCTION

Water management in irrigation districts is a complex process that depends on the availability of reliable, standardized, and georeferenced information. However, in practice, a substantial portion of the data generated within irrigation modules, including sowing dates, irrigation history, soil characteristics, phenological variables, and water stress estimates, remains dispersed across administrative files, spreadsheets, or independent systems that do not enable integrated spatial analysis. This fragmentation constrains monitoring capacity, hinders operational decision-making, and diminishes the effectiveness of internal auditing and irrigation planning processes. Open geospatial formats such as GeoJSON provide an efficient alternative for integrating and visualizing information from tabular sources in a structured manner that is compatible with Geographic Information Systems (GIS) and web viewers. Recent studies have shown that transforming data originally published in spreadsheets into interoperable geospatial models enhances accessibility, spatial analysis, and usability through open technologies and interactive viewers. Nevertheless, in agricultural contexts, its adoption remains limited due to the lack of tools capable of automating the conversion and integration of tabular and cartographic information, particularly in environments where technological infrastructure is minimal and where local, portable solutions are required. Within this context, it is essential to develop tools that enable the transformation of traditional irrigation module records into standardized, interoperable, and readily interpretable geospatial products. The automated integration of agronomic information with the cartography of agricultural plots represents a significant advance in the digitalization of irrigation services, as it facilitates the spatial analysis of water stress, the identification of operational inconsistencies, and the improvement of data traceability.

Accordingly, the aim of this study was to develop a computational tool to automatically integrate and visualize agronomic and cartographic data from the Batequis Irrigation Module through a GeoJSON file compatible with GIS platforms and web viewers, in order to strengthen irrigation operational management and facilitate geospatial analysis. The proposed system automates the processes of data normalization, linkage, and export, thereby providing a georeferenced model to improve the visualization, interpretation, and use of agricultural information in Irrigation Modules.

MATERIALS AND METHODS

Study area

Information was obtained from agricultural plots belonging to the Batequis Irrigation Module (BIM), which is part of Irrigation District 075 Río Fuerte (ID075), located in the northern region of the state of Sinaloa, Mexico. This Irrigation Module manages an area slightly below 12 thousand hectares, predominantly characterized by clay-textured soils, a feature commonly found throughout much of ID075. Agricultural activity usually begins in September, when the earliest grain crops and various vegetables are established, and concludes toward the end of December. The set of crops cultivated during the autumn-winter (A-W) cycle represents, in a highly representative manner, the productive dynamics of the entire district.

Data sources

Two principal sources were used: (1) the digital cartography of BIM crop plots in shapefile (.shp) format, which includes geometries and a unique identifier designated as "CTA"; and (2) a digital report file in Microsoft Excel format generated by water stress analysis software. This report contains, in tabular form, irrigation history, sowing dates, soil characteristics, crop phenological stages, derived variables such as readily available moisture and accumulated actual evapotranspiration, as well as the stress category ("No stress," "Low," "Medium," "High," "Severe") for each of the BIM plots. In other words, this report primarily provides the estimated water stress for each maize-cultivated plot in the A-W cycle on a given date. These two inputs constituted the basis for the automated geospatial integration process.

Development environment

The tool was developed in Python 3.11 using open-source libraries selected for their stability and compatibility with geospatial standards. The main libraries employed were Pandas, for the manipulation and filtering of tabular data; GeoPandas, for geometry management and GeoJSON product generation; and Tkinter, for the graphical user interface of the application. The system operates locally on Microsoft Windows 11 (x64) without requiring an internet connection, thereby ensuring the portability and security of the processed agricultural data.

Implementation architecture

The tool was designed using a process-oriented modular architecture in order to ensure clarity in workflow, operational stability, and ease of future expansion. Figure 1 illustrates the system structure in three functional layers that interact in a sequential and well-defined manner. The first corresponds to the data acquisition layer, responsible for the reading and initial validation of input files (shapefile and spreadsheet) through temporary structures based on GeoDataFrame and DataFrame. The second layer, referred to as the processing and transformation layer, executes the core procedures of the tool: information normalization, CTA identifier generation, geometry verification, tabular-to-spatial merging, and the automatic incorporation of derived agronomic variables. This module constitutes the core of the system, as it concentrates the logic that transforms the

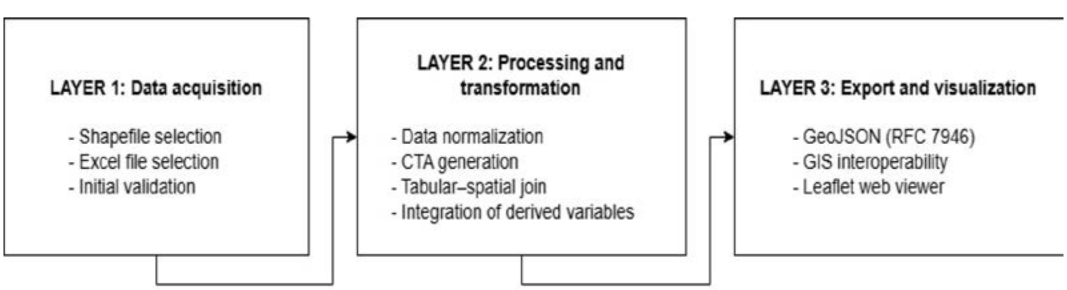


Figure 1. General system architecture, organized into layers for data acquisition, information processing, and GeoJSON file generation with web-based visualization.

operational information of the irrigation service into a coherent geospatial dataset. The third layer, corresponding to export and visualization, generates the GeoJSON file under the RFC 7946 standard and ensures its compatibility with the web viewer developed in HTML5 and Leaflet. This layered separation made it possible to maintain a flexible structure in which each component can be adjusted without affecting the operation of the rest of the system.

Standardization and matching of identifiers

Before the linking process, the datasets underwent a structural normalization procedure. The original spreadsheet was cleaned to remove duplicates and null values, and a unique identifier denominated CTA was generated from the combination of the ID_USU and ID_SUBCTA fields, which represent, in the water stress analysis report, the identifier of each plot within the Batequis Irrigation Module (BIM). This identifier made it possible to establish a direct correspondence between each tabular record and its respective polygon within the shapefile. The cartographic file was reprojected to the WGS 84 coordinate system (EPSG:4326), which is compatible with the RFC 7946 standard established by the Open Geospatial Consortium (OGC) for the GeoJSON format. During this phase, consistency checks were performed to verify the uniqueness of identifiers, the validity of geometries, and the correspondence in the number of records between both datasets.

Integration and automation workflow

The process was structured as a sequential workflow that enables the transformation of tabular irrigation service records into a geospatial product ready for analysis. The tool was developed under a modular architecture, so that each stage operates independently while remaining logically connected within a coherent sequence. The procedure begins with the selection of the input files, in which the user, through a graphical user interface, chooses the shapefile containing the delineation of agricultural plots and the spreadsheet containing the agronomic data. Subsequently, both files are read and internally interpreted as data structures, namely a GeoDataFrame for the spatial component and a DataFrame for the tabular component, in order to preserve their respective attributes and encoding formats. Once the information has been loaded, a phase of identifier normalization and matching is executed, in which the unique CTA code (account + subaccount) is used as the relational key between the table and the agronomic attributes of each plot. The process then continues with the incorporation of additional data for each plot record, including irrigation dates, phenological stages, water stress parameters, and accumulated evapotranspiration, which are automatically integrated whenever they are available in the tabular database. Finally, the consolidated information undergoes an automated export phase, in which the user defines the location of the output file and the tool generates the final product in GeoJSON format. This methodological workflow is summarized schematically in Figure 2, which illustrates the principal stages of selection, processing, and automated generation of the geospatial product.

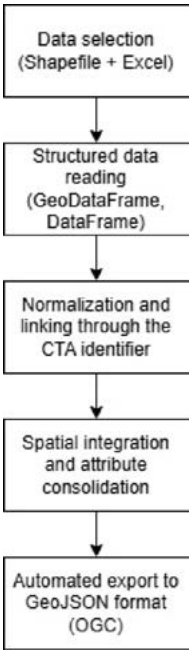


Figure 2. Schematic representation of the methodological workflow for the automated integration of tabular and spatial data through the Python-based tool developed in this study.

Validation of the GeoJSON product

Validation was designed to ensure the structural, spatial, and semantic reliability of the resulting dataset. This process was intended to verify that the information contained in the file preserved geometric integrity, maintained the consistency of agronomic attributes, and complied with international geospatial interoperability standards. Structural verification was carried out using control functions included in the GeoPandas library, together with online format validation tools, in order to ensure that the file complied with the RFC 7946 specification established by the Open Geospatial Consortium (OGC).

Interactive web visualization

As a complement to the integration stage, an interactive web visualization component was developed for the geospatial exploration of the generated GeoJSON files. The implementation of this viewer was based on HTML5 and the Leaflet.js library, together with OpenStreetMap basemaps, in order to represent agricultural plots directly within a web environment without the need to install specialized software. The application was designed to operate locally and to provide a simple interface through which the user can upload a GeoJSON file and immediately visualize the spatial distribution of agricultural plots on the map.

Software usability and functionality

Software quality was evaluated through two dimensions, usability and functionality, which contribute to understanding both the user's interaction experience with the system and the technical adequacy of the implemented functions for the integration and visualization of agronomic information. The use of both methods is consistent with literature-based practices for the evaluation of information systems in technical and operational domains.

Evaluation design

The evaluation was structured under a descriptive experimental methodology. Through direct interaction with the tool, participants performed representative tasks reflecting the actual use of the system, particularly the integration of agronomic and cartographic data and the generation of the geospatial product. Subsequently, users completed the corresponding evaluation instruments, following an approach frequently employed in software assessment studies.

Participants

The test was conducted with the participation of seven experts in agronomy, specifically in irrigation management, soils, and agricultural information analysis. Participants were selected on the basis of their familiarity with irrigation operational processes and the use of digital tools; therefore, their assessments were grounded in technical and operational criteria appropriate to the context of the study.

Evaluation instruments

System usability was assessed using the System Usability Scale (SUS), proposed by Brooke (1996), which consists of ten items and employs a five-point Likert scale, where 1 represents "strongly disagree" and 5 represents "strongly agree." The SUS yields an overall usability score on a scale from 0 to 100 and has proven to be a robust and widely accepted instrument for evaluating user experience across diverse technological contexts. Its application in web systems and digital platforms has been documented in recent studies, confirming its validity and methodological consistency. In addition, an instrument based on the domain quality model, specifically the ISO/IEC 25010 quality model, was employed to evaluate software functionality, with emphasis on its functional suitability subcharacteristic. This strategy was adopted because the standard provides a conceptual framework for software quality evaluation but does not define a specific questionnaire; therefore, it is methodologically valid to design context-specific instruments. The instrument consisted of eight items designed to assess the completeness of functions, the correctness of generated results, the operational reliability of the system, and its relevance for irrigation and water stress analysis, using a five-point Likert scale.

Procedure

The procedure began with a system-use session in which participants worked through the basic functions of the tool, including input file selection, agronomic and cartographic data integration, GeoJSON file generation, and the visualization of results through the web viewer. Upon completion of these tasks, the usability and functionality questionnaires were administered through a Google Forms survey designed for individual response.

Data analysis

Descriptive statistics were used to organize the data obtained from both instruments. For the SUS questionnaire, the overall score was calculated according to the procedure described by Brooke (1996), through which values were obtained on a scale from 0 to 100. Measures of central tendency and dispersion were calculated, as well as the percentage of functional compliance for the instrument developed on the basis of the data obtained using the ISO/IEC 25010 model.

RESULTS AND DISCUSSION

Geospatial integration and generation of the GeoJSON product

The developed tool enabled the integration of agronomic and cartographic information from the Batequis Irrigation Module into a single geospatial product, while preserving the integrity of the geometries and the coherence of the attributes associated with each plot. The generated GeoJSON file maintained complete correspondence between tabular records and polygons through the CTA identifier, thereby confirming the effectiveness of the normalization, linkage, and export workflow described above.

This result demonstrates that the automated process is suitable for transforming information traditionally dispersed across spreadsheets into an interoperable georeferenced model, a condition regarded as essential for improving traceability and spatial analysis in agricultural irrigation systems, as reported by John and James (2025), Zhao *et al.* (2023), and Espinel *et al.* (2024).

Georeferenced visualization of water stress

The web-based visualization made it possible to spatially represent water stress levels at the plot scale, thereby facilitating a territorial interpretation of crop status within the irrigation module. The viewer displays agricultural plots using thematic symbology associated with the water stress category (Figure 3), which enables the immediate identification of areas exhibiting different hydric conditions. Furthermore, the spatial distribution of the plots reveals stress concentration patterns, which is particularly useful for guiding monitoring actions, prioritizing field inspections, or revising irrigation scheduling. This type of representation has been reported as an effective tool for translating technical indicators into operational information that is readily understandable for users in the agricultural sector (Ennatiqi *et al.*, 2024; Piccoli *et al.*, 2023; Radulović *et al.*, 2025).

Detailed query of agronomic information by plot

The web viewer allows access to plot-specific information through pop-up windows. When a polygon is selected, key agronomic attributes are displayed, including the CTA identifier, soil type, sowing dates, phenological stage, accumulated evapotranspiration, readily available moisture, and supplementary irrigation records (Figure 4). Likewise, this functionality demonstrates that the system consolidates, within a single visual environment, information that is normally dispersed across different administrative reports. From an operational perspective, such integration facilitates precise data verification and the early detection of potential inconsistencies, which is consistent with findings reported for other

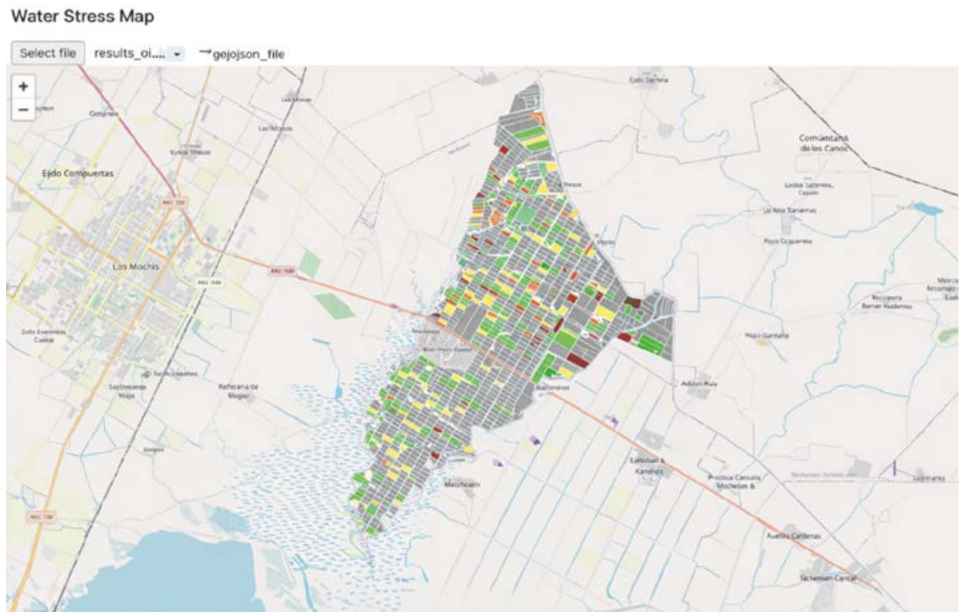


Figure 3. Graphical interface of the web application for visualization.

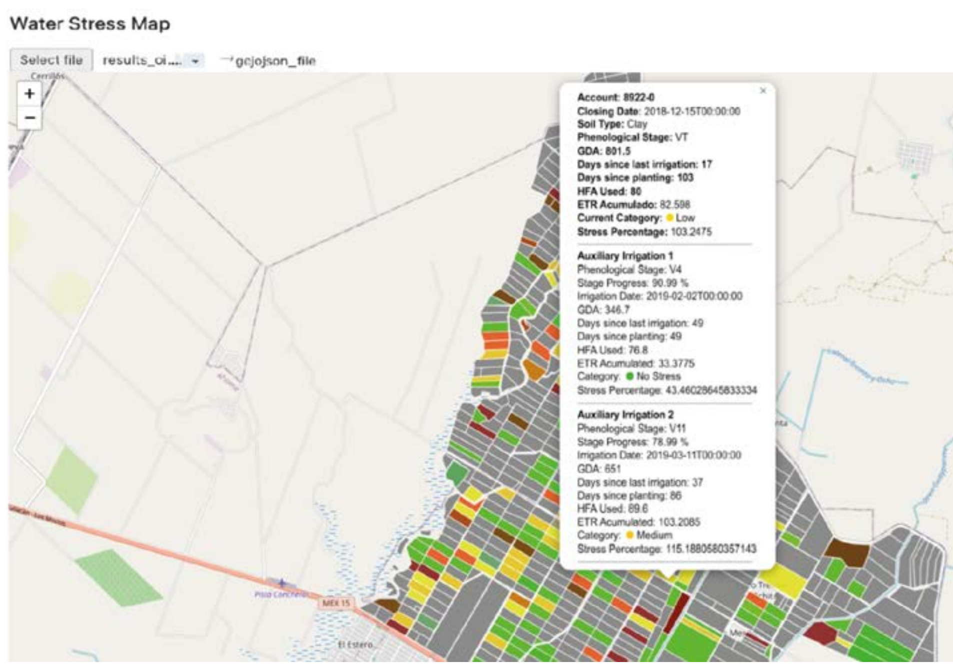


Figure 4. Interactive informational pop-up displaying details of the plot selected by the user.

GIS-based agricultural decision-support systems (Ezzahri *et al.*, 2024; Raihan, 2024; Panda *et al.*, 2025).

System usability evaluation

The individual scores obtained from the usability test through the SUS questionnaire, administered to seven specialists with experience in agronomy and irrigation management, are presented in Table 1, where it can be observed that all values remained within a high range.

The statistical summary of the results is presented in Table 2. The mean score was 82.5 (SD=3.02), which places the system within the Excellent category according to the SUS interpretation criteria proposed by Brooke (1996) and Bangor *et al.* (2008).

As reported in the literature, SUS values above 80 indicate a high probability of user acceptance of the system (Rofiansyah *et al.*, 2025). In this case, the low dispersion of the results suggests a homogeneous perception among the specialists, which further reinforces the reliability of the evaluation.

Functionality evaluation based on ISO/IEC 25010

The functionality of the software was evaluated using an instrument derived from the ISO/IEC 25010 model, with particular emphasis on the functional suitability subcharacteristic. The results by criterion are presented in Table 3, where a high level of compliance can be observed across all evaluated aspects.

The overall average of 4.7 out of 5, equivalent to 94% functional compliance, indicates that the system adequately satisfies the requirements for which it was designed. These results are consistent with studies that use software quality models as conceptual frameworks to evaluate specific systems without imposing rigid instruments, thereby allowing adaptations to the application context (Gañgan, 2025; Catigday *et al.*, 2025). The convergence of the results related to geospatial integration, visualization, usability, and functionality suggests that the tool not only fulfills the technical requirements, but is also operationally viable for

Table 1. Individual SUS questionnaire scores.

Evaluator	SUS score
E1	80.0
E2	82.5
E3	85.0
E4	87.5
E5	78.0
E6	84.0
E7	80.5

SUS=System Usability Scale; E=Evaluator.

Table 2. Descriptive statistics of the SUS score.

Indicator	Value
Number of evaluators	7
Minimum score	78.0
Maximum score	87.5
Mean	82.5
Standard deviation	3.02
SUS classification	Excellent

SUS=System Usability Scale.

Table 3. Results of the system's functional evaluation (ISO/IEC 25010).

Evaluated criterion	Mean	SD
Functional completeness	4.8	0.20
Result correctness	4.6	0.24
Operational reliability	4.7	0.22
Relevance for irrigation analysis	4.8	0.22
Overall average	4.7	0.21

ISO/IEC 25010=Systems and software quality requirements and evaluation model; SD=Standard deviation.

use in real irrigation management contexts. Figures 3 and 4 illustrate how the generated products can be directly interpreted by specialists, while Tables 1, 2, and 3 provide quantitative support for this perception from the user's standpoint. In comparison with other studies focused on the digitalization of agricultural water management, the results obtained are consistent with the evidence highlighting the importance of integrating spatial data, agronomic analyses, and accessible tools to strengthen decision-making in irrigation districts (Flores-Mancheno & Palacios-López, 2025; Fuentes-Peñailillo *et al.*, 2025; Escandón-Panchana *et al.*, 2024).

CONCLUSIONS

The developed system enabled the automated integration of agronomic and cartographic information from the Batequis Irrigation Module into an interoperable GeoJSON file, while maintaining correspondence between spreadsheet-based tabular records and the geometries of agricultural plots. The implemented process facilitated the standardization, linkage, and geospatial visualization of data related to irrigation management and water stress.

The developed tool generates functional and consistent products that can be visualized and interpreted through GIS platforms and web viewers without requiring specialized infrastructure. The spatial representation of water stress made it possible to clearly identify the distribution of hydric conditions at the plot level, thereby providing useful operational information for irrigation management. The usability and functionality evaluation indicated favorable acceptance of the system by specialists, demonstrating that the tool is understandable, operationally appropriate, and aligned with the requirements of agricultural irrigation analysis. Taken together, the results confirm that the proposed solution fulfills the stated objectives and exhibits both the technical and operational conditions necessary for potential implementation in other Irrigation Modules and Irrigation Districts facing similar challenges, particularly in regions affected by water scarcity.

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