

A DIGITAL TWIN FRAMEWORK FOR PLOT-SCALE IRRIGATION MANAGEMENT

UN CADRE DE JUMENTO NUMÉRIQUE POUR LA GESTION DE L'IRRIGATION À L'ÉCHELLE DE LA PARCELLE

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ABSTRACT

Efficient irrigation management increasingly requires integrated tools capable of combining field observations, spatial variability, and process-based modelling within a single operational environment. This work presents the development of a modular Digital Twin (DT) framework for precision irrigation, implemented within the QGIS environment.

The proposed framework integrates hydraulic simulation, sensor data, agro-climatic information, satellite imagery, canopy cover estimation, irrigation scheduling, and AquaCrop-based crop modelling into a single operational architecture. The system is structured into interoperable modules, including a Hydraulic Module based on EPANET, a Sensors Module for managing heterogeneous real-time and near-real-time data streams, an Irrigation Module based on a FAO-56 daily soil water balance, a Satellite Image Module, a Canopy Cover estimation module, and an AquaCrop Spatial Module for pixel-based crop simulation. DT enables the configuration of hydraulic and agronomic scenarios, the incorporation of sensor and climatic data, the estimation of spatially varied canopy cover from satellite imagery, and the generation of crop performance outputs such as canopy development, biomass, and yield. The resulting prototype provides an integrated environment for monitoring and simulating irrigation performance under different management and climatic conditions to make informed management decisions.

Keywords: precision irrigation; remote sensing; AquaCrop; EPANET; canopy cover; decision support system.

RÉSUMÉ

La gestion efficace de l'irrigation nécessite de plus en plus des outils intégrés capables de combiner les observations de terrain, la variabilité spatiale et la modélisation fondée sur les processus au sein d'un environnement opérationnel unique. Ce travail présente le développement d'un cadre modulaire de jumeau numérique (DT) pour l'irrigation de précision, mis en œuvre dans l'environnement QGIS.

Le cadre proposé réunit, dans une architecture opérationnelle unique, la simulation hydraulique, les données de capteurs, les informations agroclimatiques, l'imagerie satellitaire, l'estimation de la couverture végétale, la programmation de l'irrigation et la modélisation des cultures fondée sur AquaCrop. Le système est structuré en modules interopérables, notamment un module hydraulique fondé sur EPANET, un module de capteurs destiné à gérer des flux de données hétérogènes en temps réel et quasi réel, un module d'irrigation fondé sur un bilan hydrique journalier du sol selon FAO-56, un module d'imagerie satellitaire, un module d'estimation de la couverture végétale et un module spatial AquaCrop pour la simulation des cultures à l'échelle du pixel. Le DT permet de configurer des scénarios hydrauliques et agronomiques, d'intégrer des données de capteurs et des données climatiques, d'estimer à partir d'images satellitaires la couverture végétale et sa variabilité spatiale, et de produire des résultats sur les performances des cultures, tels que le développement du

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couvert, la biomasse et le rendement. Le prototype obtenu offre un environnement intégré pour surveiller et simuler les performances de l'irrigation selon différentes conditions de gestion et différents contextes climatiques, afin d'éclairer les décisions de gestion.

Mots clés : Irrigation de précision; Télédétection; AquaCrop; EPANET; Couvert végétal; Système d'aide à la décision.

1. INTRODUCTION

Water scarcity has become one of the main constraints on agricultural sustainability, particularly in irrigated systems, where production depends directly on the availability and efficient management of water resources. (Zhang et al., 2025). Population growth, urban expansion, industrial development, and climate change are intensifying pressure on freshwater resources worldwide, while increasing competition among sectors is narrowing the margin for agricultural water use. Since agriculture accounts for the largest share of global freshwater withdrawals, approximately 70%, (Atalay, 2023) improvements in irrigation management are essential not only for maintaining productivity, but also for ensuring the long-term resilience of food production systems under increasingly restrictive environmental conditions. These challenges are especially critical in contexts where water availability is becoming more uncertain. Climate variability is modifying precipitation patterns, increasing the occurrence of droughts, and making irrigation planning more complex at both plot and farm scales (Abioye et al., 2020).

Under these conditions, irrigated agriculture must respond to a dual challenge: increasing or sustaining crop production while reducing water use and adapting to a more variable and less predictable climate. Meeting this challenge requires moving beyond conventional irrigation scheduling approaches and towards management strategies that can capture the physical, spatial, and temporal complexity of irrigated systems. In recent years, precision irrigation has advanced significantly using in-field sensors, IoT technologies, remote sensing products, and digital data platforms. These tools have improved the capacity to observe field conditions and monitor system performance with a level of detail that was previously unavailable. However, the availability of data alone does not guarantee better irrigation decisions. One of the main limitations remains the lack of integrated operational frameworks capable of combining heterogeneous information sources with process-based models in a way that is useful for diagnosis, simulation, and decision support (Dawn et al., 2024).

Irrigation management requires not only data collection, but also the ability to interpret that information in relation to hydraulic behavior, spatial variability in water application, and crop response to different management scenarios. Within this context, DT has emerged as a promising approach for the development of advanced irrigation management tools. A DT is a dynamic virtual representation of a physical system that is continuously updated with observed data and linked to simulation models. In irrigation systems, this approach offers clear potential because it allows infrastructure performance, field observations, and crop behavior to be analyzed within a single framework. By reproducing the state and functioning of the real system in a virtual environment, a DT can support continuous monitoring, identify operational constraints, and enable the evaluation of management alternatives before they are implemented in the field. In response to these challenges, this work presents a framework for the creation and implementation of DT for precision irrigation at plot scale.

The proposed approach integrates hydraulic modelling, climate analysis, remote sensing, in-field monitoring, and crop simulation into a unified architecture designed to support monitoring, scenario analysis, and decision-making. By combining these components within a single digital environment, this framework aims to contribute to more efficient and adaptive irrigation management, while providing a practical basis for improving water use efficiency and strengthening the resilience of irrigated agriculture under increasing external constraints.

2. MATERIALS AND METHODS

A DT was developed within the QGIS environment, which served as the main platform for data integration, spatial processing, visualization, and interaction among the different components. The overall framework is based on a set of interoperable modules implemented in Python, allowing the integration of field information, remote sensing products, sensor observations, hydraulic simulation, and crop modelling into a single operational architecture. Figure 1 presents the general structure of the proposed Holistic Digital Twin for Precision Irrigation (HDT-PI). Blue arrows indicate external and user-provided data entering the DT, solid black arrows represent an output pathway, and dashed arrows denote secondary exchanges and feedback interactions between modules. The architecture was designed following a modular approach, in which each component performs a specific function while continuously exchanging information with the others. This structure makes it possible to combine heterogeneous data sources and simulation tools to represent irrigation processes at plot scale in a dynamic and spatially explicit way.

2.1 External data

HDT-PI receives information from user-defined inputs and external data streams. User-defined inputs include hydraulic data, network geometry, soil data, crop data, initial canopy cover and initial field conditions. Hydraulic and network data define the irrigation infrastructure layout and provide the information required by the Hydraulic Module to simulate system behavior. Regarding soil information it can be introduced as fixed texture values, spatial soil layers, or predefined soil classes, allowing the framework to adapt to different levels of data availability. In addition, initial soil water content may be obtained from in-field soil moisture sensors or introduced manually, while additional initial conditions such as soil depth, salinity, and canopy cover are defined by the user. The initial canopy cover (CC) may also be specified by the user when known. For crop definition, the user selects the crop type from a predefined list and specifies the sowing date and simulation period. External data streams are incorporated through Application Programming Interfaces (APIs) and include data from local sensors (soil moisture, pressure sensors, etc.) climate stations, and remote sensing platforms.

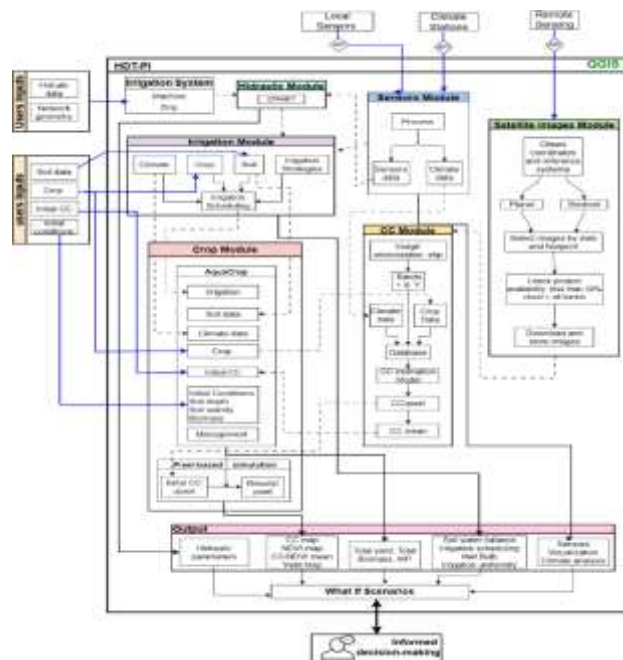


Figure 1. HDT-PI Architecture

2.2 Hydraulic Module

The Hydraulic Module based on EPANET (Rossman, s. f.) is aimed to represent the physical behavior of the irrigation network. This module requires the characteristics of the irrigation system, including the irrigation method and machine configuration, to simulate its hydraulic behavior (flow rates and pressure distributions) and calculate performance irrigation indicators. It is possible to perform real-time hydraulic simulations using sensor data, such as pressure data. This information is obtained from Sensors Module. Furthermore, this module enables the exploration of alternative network configurations by modifying parameters such as pipe material, number of pipes, pipe diameter, emitters curve or pressure levels. These scenarios can be visually compared through graphs, allowing the analysis of hydraulic variables, such as flow rate, pressure, head loss, velocity, etc., under different operating conditions. Its outputs are used to assess the operational condition of the system and to support irrigation scheduling by accounting for hydraulic constraints and irrigation uniformity.

2.3 Sensors Module

To incorporate in-field observations, the Sensors Module enables the acquisition, processing, and integration of data from soil sensors, irrigation system sensors, and external agroclimatic networks. It connects with commercial APIs from different sensor manufacturers, allowing heterogeneous data streams to be accessed in a standardized way and used within the HDT-PI environment. An important aspect of this module is its capacity to manage data streams with different temporal resolutions. Each sensor or data source may provide information at a different frequency; for example, soil moisture sensors may record data every 30 minutes, pressure sensors every 15 minutes, whereas agroclimatic stations often provide daily observations. The Sensors Module therefore harmonizes these heterogeneous temporal scales, organizing the data according to their acquisition frequency and making them available in a consistent format for the other HDT-PI components. This temporal management is essential to ensure that real-time hydraulic variables, soil water status, and daily climatic information can be jointly used within a single modelling framework. In addition, it provides automated access to historical and forecast weather data according to the plot location and performs a hydrological analysis of historical series to classify years as dry, average, or wet. This information continuously updates the system and improves the consistency between simulated and observed field conditions.

2.4 Irrigation Module

The Irrigation Module was designed to perform the main agronomic calculations required for irrigation management, including irrigation scheduling, wetted bulb dimensions, and irrigation suitability assessment. Its core is a dynamic daily soil water balance based on the FAO-56 approach (Allan et al., 1998), which estimates soil water content at the end of day i as:

$$SW_i = SW_{i-1} + Pe_i + I_i - ETc_i - DP_i \quad (1)$$

Where i is the daily index for the irrigation campaign, Pe is effective precipitation, I is net irrigation, ETc is crop evapotranspiration, and DP is deep percolation. This module combines four main sources of information: irrigation strategy, climatic inputs, soil moisture status, and crop variables. Irrigation can be simulated under different management strategies, including Maximum Irrigation Requirements (MIR), Controlled Deficit Irrigation (CDI), and Sustained Deficit Irrigation (SDI). The initial soil moisture condition can be defined either by the user or from real-time data acquired from local soil moisture sensors. The Rosetta soil pedotransfer model (Schaap et al., 2001) was implemented to determine the hydraulic soil parameters from the available soil texture information. This information is required for both, the soil water balance model (Irrigation Module) and the AquaCrop model. To incorporate climatic uncertainty, this module is connected to the sensor module and uses the hydrological classification (selected by the users) to simulate irrigation schedules under varying climatic scenarios. Crop selection also activates the crop-specific parameters required by the module, including monthly crop coefficient values (Kc), the depletion fraction according to the FAO-56 approach, among others. The outputs of this module provide a daily irrigation forecast from the current day up to five days

ahead (based on ET_c and Pe forecasts), according to the selected climatic scenario and irrigation strategy.

2.5 Satellite Image Module

A second monitoring component corresponds to the Satellite Images Module, which manages the acquisition and preprocessing of remote sensing data. This module retrieves images from platforms such as Sentinel (Copernicus Data Space Ecosystem, 2026) and Planet (Planet Team, 2026) according to the user selection, using the plot coordinates and reference system defined in QGIS. Image acquisition is performed through the corresponding API of each platform, allowing the integration of both open-access satellite products, such as Sentinel, and commercial imagery, such as Planet. These platforms provide data with different spatial, spectral, and temporal resolutions, which allows the HDT-PI to be adapted to different monitoring requirements and levels of detail. Images are filtered according to acquisition date, spatial footprint, cloud cover, and band availability before being downloaded and processed. This procedure ensures that only suitable remote sensing products are incorporated into the HDT-PI workflow.

2.6 Canopy Cover module

The Canopy Cover Module provides spatially distributed estimates of crop canopy cover (CC) for integration into the HDT-PI. It processes the satellite images obtained from the Satellite Module, extracting pixel-level spectral bands and combines them with coordinates growing degree days (GDD) derived from crop and climate data. These variables form the input database for the CC estimation model. Figure 2 describes the model flow chart.

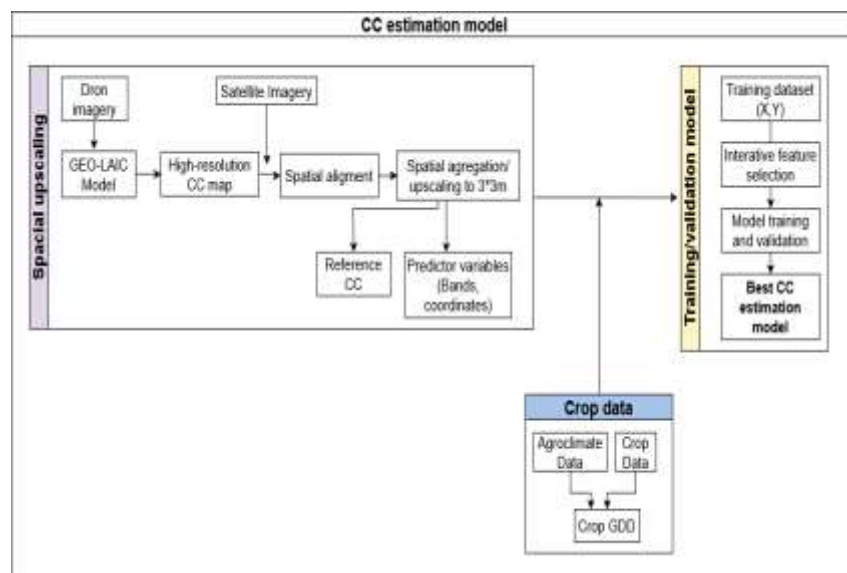


Figure 2. CC estimation model

CC estimation model used Planet satellite imagery at 3 m by 3 m spatial resolution and centimetre-scale drone imagery as reference data. Drone-derived CC maps were obtained with GEO-LAIC (Córcoles et al., 2013) and spatially aggregated to match the Planet pixel size after image alignment. These upscaled CC values were used as ground-truth data to train and validate of the CC estimation models.

The predictive variables used in the modelling process included eight spectral bands from the satellite imagery, eight vegetation indices (NDVI, GNDVI, OSAVI, EVI, NDRE, NIRv, kNDVI, and CI_RedEdge) (Montero et al., 2023), geographical coordinates and GDD.

To identify the most informative set of predictors, an iterative feature selection procedure was carried out. Different combinations of input variables were tested sequentially, and the final selection was based on the maximization of model performance and generalization capability. Using this dataset, four machine learning algorithms were trained and validated for CC estimation. The best-performing model was then selected and incorporated into the DT for operational estimation of CC at plot scale.

Within the HDT-PI architecture, this module uses the selected estimation model to derive CC values per pixel from incoming satellite imagery. These CC estimates are subsequently transferred to the pixel-based simulation in the Crop Module, where they are used either as direct spatial outputs or as state variables for crop simulation, calibration, and predictive analyses.

2.7 Crop Module

2.7.1 Aquacrop model

The Crop Module of the proposed DT is based on AquaCrop (*AquaCrop on the Ground*, 2025), a crop water productivity model developed by the Food and Agriculture Organization of the United Nations (FAO) to simulate crop response to water availability under different climatic and soil conditions. AquaCrop is especially suitable for irrigation-related applications because of its explicit focus on the relationship between water use, biomass production, and yield. In contrast to many crop growth models, AquaCrop uses a relatively limited number of explicit parameters and mostly intuitive input variables, which facilitates its implementation in operational decision-support environments (Puig et al., 2025).

The model simulates crop development and expected yield through a sequential four-step procedure: (i) canopy cover development, (ii) crop transpiration, (iii) above-ground biomass accumulation, and (iv) final yield estimation through the harvest index. A key feature of AquaCrop is the use of CC rather than leaf area index (LAI) to describe crop development. Within the model, CC is the central variable controlling the partition between soil evaporation and crop transpiration and therefore has a direct influence on biomass accumulation and final yield. The theoretical development of CC is represented through early canopy expansion, late growth until maximum canopy cover, and decline associated with senescence. Under conditions of stress, low fertility, salinity, or extreme temperatures, the model applies stress coefficients to slow vegetative growth or accelerate canopy decline. Once CC development is defined, AquaCrop estimates crop transpiration as:

$$Tr = K_s \cdot K_{c_{Tr}} \cdot ET_0 \quad (2)$$

where Tr is crop transpiration, K_s is the water stress coefficient, $K_{c_{Tr}}$ is the crop coefficient for transpiration, calculated as the product between $K_{c_{Tr,x}}$ maximum transpiration coefficient and CC, and ET_0 is the reference evapotranspiration. The accumulated above-ground biomass is then estimated from the normalized crop water productivity parameter (WP) and the ratio between transpiration and reference evapotranspiration:

$$B = WP \cdot \sum \frac{Tr}{ET_0} \quad (3)$$

Finally, crop yield is calculated from biomass using the harvest index (HI):

$$Y = HI \cdot B \quad (4)$$

This modelling structure is particularly useful within the DT framework, since it allows direct coupling between water management decisions and crop performance.

2.7.2 Aquacrop input files

In the HDT-PI, the input files required by AquaCrop are automatically generated from the outputs of the other modules. The irrigation file is generated from the irrigation scheduling results produced by the Irrigation Module. Once the user defines the crop simulation period, the Irrigation Module creates the irrigation schedule for the entire simulation time window. The soil file is generated from the hydraulic parameters estimated by the Rosetta pedotransfer model, while the climate file is built from the meteorological data managed by the Sensors Module. The initial conditions file is created from the information provided by the user and from the internal logic of the HDT-PI. A specific clarification is required for the initial canopy cover.

This variable can be: (i) directly defined by the user, (ii) internally simulated by AquaCrop, or (iii) obtained from the Satellite Images Module through remote sensing products. Because AquaCrop is highly sensitive to CC, special attention was given in this study to the correct specification of this variable. In addition, DT includes a library of previously validated and calibrated crop files, which can be selected directly by the user. This reduces model setup effort and ensures that crop parameterization is based on tested configurations. The variable Kc is obtained, for each crop, from the information of the crop in irrigation module.

2.7.3 Simulation procedure

The Crop Module allows the prediction of final crop yield from the current state of an existing crop. Figure 3 describes how the simulation is performed.

The user starts from the current state of an existing crop at a given day i . A satellite image acquired on that day is used to estimate the actual canopy cover of the crop. This observed CC value is then introduced into AquaCrop as the initial canopy condition for a forward simulation aimed at predicting crop performance up to harvest. However, using only the observed canopy cover is not sufficient, because AquaCrop also requires internally consistent values for state variables such as accumulated biomass and rooting depth. To address this issue, the HDT-PI first performs an internal simulation from the sowing date to the date of the satellite image. From this preliminary run, the model obtains the corresponding values of biomass and effective root depth at day i . These variables are then used as the initial state for the predictive simulation, together with the observed canopy cover derived from remote sensing. In this way, the HDT-PI combines real field information with model-consistent internal states, resulting in a more realistic forecast of final yield.

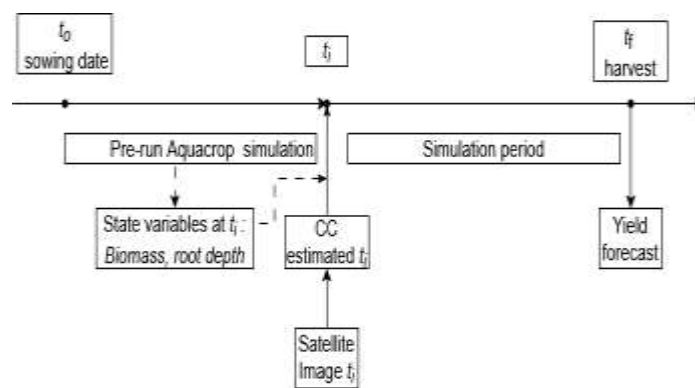


Figure 3. Predictive simulation procedure integrating remotely sensed CC with AquaCrop state variables.

2.8 Pixel-based simulation

Pixel-based simulation explicitly extends the crop simulation from a field-average approach to a pixel-based representation. Its main function is to encapsulate the AquaCrop model and execute it independently for each pixel within the plot. For this purpose, the module uses the CC estimated for

each pixel and grouped into classes or bins. These values are used as the corresponding initial CC condition, thereby allowing the simulation to account for within-field spatial variability in crop development. Through this approach, each pixel is treated as an individual simulation unit with its own initial crop state, while maintaining consistency with the general soil, climate, and management conditions defined for the parcel. As a result, the module generates spatially distributed outputs of crop performance, making it possible to derive maps of variables such as canopy cover, biomass, and yield, and to analyze the heterogeneity of crop response across the field.

3. RESULTS

The implementation of the HDT-PI resulted in an operational interface integrated within the QGIS environment, where the different modules of the system can be accessed, configured, and executed from a single spatial platform. The interface was designed to support the complete workflow required for plot-scale irrigation management, from the definition of the study area and input data to the visualization of model outputs and spatial results.

Figure 4 shows the HDT-PI interface for a drip irrigation system. The figure illustrates the set of configurable parameters that can be modified to generate and evaluate different hydraulic scenarios, including parameters related to the hydrant, main line, submain, and laterals. In addition, the map view displays the connected sensors within the plot together with their most recent measurements, providing real-time information on field conditions and system operation.

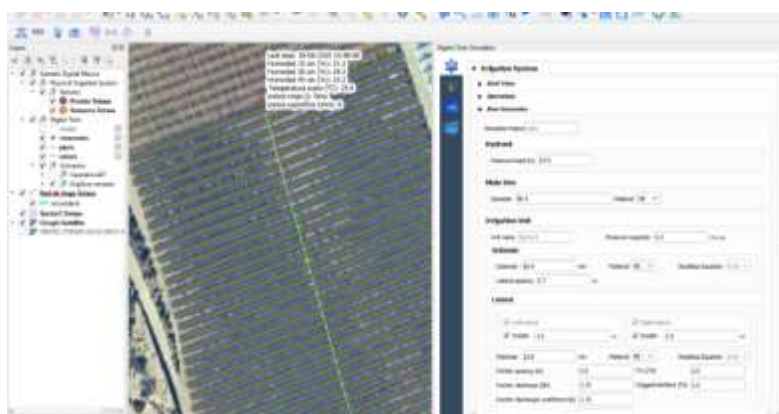


Figure 4. QGIS-based interface of the Digital Twin for setting hydraulic scenarios in a drip irrigation system

Figure 5 presents the irrigation and crop modelling configuration interfaces of the DT, through which the user defines the main agronomic, soil, and management inputs required to initialize the simulation workflow. Through this panel, the user can select the crop type, introduce or select soil information, configure the irrigation management strategy, define the sowing date, simulation period and initial conditions. These inputs are automatically connected with the internal modules responsible for generating the AquaCrop input files, estimating soil hydraulic properties, retrieving climatic data, and calculating irrigation requirements. In this way, the interface reduces the need for manual preparation of separate model files and provides a direct link between field information, model parameterization, and simulation outputs.

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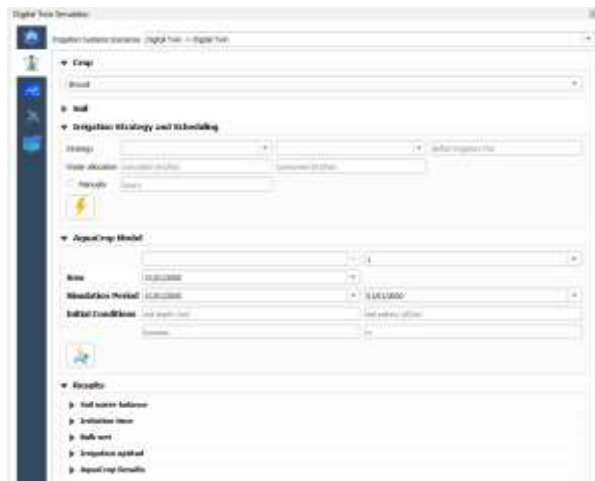


Figure 5. Irrigation and crop modelling configuration interface

Figure 6 presents the Satellite Image Module interface, which enables the selection and download of satellite imagery for the study plot. Once the images are retrieved, the module automatically processes the available spectral information and computes summary indicators such as mean NDVI and mean canopy cover for each acquisition date. These outputs are displayed both as spatial products and as graphical time series, allowing the user to monitor crop development throughout the growing season. Figure 6 shows the climatic data interface, where information can be obtained either from the nearest agro-climatic station or from user-installed field sensors. This module displays the resulting meteorological time series and performs a climatic analysis of the selected period, providing the input information required for irrigation scheduling and crop simulation.



Figure 6. Satellite Image Module interface for image download and CC processing.

CONCLUSIONS

This work presents a modular DT framework named Holistic Digital Twin for Precision Irrigation for plot-scale irrigation management, integrating hydraulic simulation, sensor observations, agro-climatic data, satellite imagery, canopy cover estimation, irrigation scheduling, and AquaCrop-based crop

modelling within a QGIS environment. The proposed framework provides an operational structure for connecting heterogeneous data sources with process-based models, enabling the configuration of hydraulic and agronomic scenarios, the visualization of field information, and the spatially explicit simulation of crop development and irrigation performance. The developed tool demonstrates the potential of DT to link the behavior of physical irrigation systems with soil and crop processes under changing atmospheric conditions, supporting more integrated and adaptive decision-making for precision irrigation.

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