



Article

Soqia: A Responsive Web Geographic Information System Solution for Dynamic Spatio-Temporal Monitoring of Soil Water Status in Arboriculture

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Abstract: The optimization of irrigation in arboriculture holds crucial importance for effectively managing water resources in arid regions. This work introduces the development and implementation of an innovative solution named ‘Soqia’, a responsive WEB-GIS web application designed for real-time monitoring of the water status in arboriculture. This solution integrates meteorological data, remote sensing data, and ground sensor-collected data for precise irrigation management at the agricultural plot level. A range of features has been considered in the development of this WEB-GIS solution, ranging from visualizing vegetation indices to accessing current weather data, thereby contributing to more efficient irrigation management. Compared to other existing applications, ‘Soqia’ provides users with the current amount of water to irrigate, as well as an estimated amount for the next 8 days. Additionally, it offers spatio-temporal tracking of vegetation indices provided as maps and graphs. The importance of the Soqia solution at the national level is justified by the scarcity of water resources due to increasingly frequent and intense drought seasons for the past years. Low rainfall is recorded in all national agricultural areas. The implemented prototype is a first step toward the development of future innovative tools aimed at improving water management in regions facing water challenges. This prototype illustrates the potential of Web-GIS-based precision irrigation systems for the rational use of water in agriculture in general and arboriculture in particular.

Keywords: reactive WEB-GIS; crop water status; spatio-temporal monitoring; arboriculture; evapotranspiration; vegetation indices



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1. Introduction

Water represents an essential need for human beings, vital for hydration, sanitation, and hygiene, playing a crucial role in the preservation of life and human health [1]. The report released by the World Meteorological Organization provides an alarming overview of the consequences of climate, environmental, and social changes on the planet’s water reserves. This report highlights below-average precipitation in extensive regions worldwide, influenced by climate change and various other factors [2]. And the same goes for Morocco where water resources are limited, posing a significant challenge to agricultural productivity [3]. Globally, water usage is typically distributed across three sectors: industry (20%), domestic needs (10%), and agriculture (70%). These proportions vary significantly based on the development level of countries. In Morocco, over 87% of freshwater is allocated to agriculture [4]. In this context, the major challenge for the coming decades lies in the need to increase food production while using less water, requiring an improvement in irrigation efficiency [5].

Irrigation, defined as the intentional application of water to cultivated land, aims to address deficits in precipitation and/or soil water reserves, promoting optimal plant

growth [6]. This practice involves the artificial distribution of water to offset soil moisture deficits, enhance environmental conditions, and apply nutrients and phytopharmaceutical products [7].

Precision irrigation has emerged as a promising solution to achieve this goal. It aims to provide the exact amount of water needed, tailored to the specific needs of crops. However, its implementation requires a better understanding of crop conditions and anticipation of water needs. It is in this context that the emergence of digital solutions becomes crucial to support farmers in managing irrigation [8].

Examples of these applications are presented in Table 1, where we compare services provided by each application, input data used, and crop types targeted. Strengths and weaknesses of these applications were identified by examining descriptions and documentations and considering user reviews.

In computer science, an application is a program developed for a specific task, whether it involves calculations, management, or entertainment [9]. Many digital irrigation applications have been developed. A review can be found in [10,11]. In the present study, applications listed in Table 2 have been thoroughly tested and analyzed based on users' experience. Most of the applications were downloaded on our devices to be tested and evaluated. However, for applications that were inaccessible for download, the analyses were carried out based on available sources such as commercial description and users' feedback.

Table 1. Examples of spatio-temporal monitoring and farm advisory solutions for irrigation.

Application Name	Services	Input Data	Crop Types
AquaEdge [12]	<ul style="list-style-type: none"> - Receive advice on how to better manage water and energy consumption, as well as the use of water. - Daily calculation of water requirements (watering time) for each sector. - Weather forecasts, stress levels, soil moisture, and temperature. 	<ul style="list-style-type: none"> - Crop type - Plot boundaries - Meteorological data - Satellite images - Data from connected sensors - Planting density - Planting date - Cycle start date - Organic matter 	<ul style="list-style-type: none"> - Cereal crops such as wheat, corn, rice, barley, oats. - Vegetables: vegetables, mushrooms. - Fruit crops such as apple and citrus trees.
IrriSMART [13]	<ul style="list-style-type: none"> - Regularly monitor the operation throughout the crop cycle. - Help optimize drip irrigation in the field with 5 key output parameters. - Keep a history of irrigation records for each plot and each crop. 	<ul style="list-style-type: none"> - Plot boundaries - Crop type - Climatic data - Spatial data - Start and duration of vegetation period - Dripper flow rate and spacing of lines and drippers - Soil characteristics 	<ul style="list-style-type: none"> - A wide range of vegetable crops (commonly grown in the country): market garden crops, fruit crops, cereal crops. <p>Ex.: onion, potato, melon, beet, watermelon, sugar beet, carrot, garlic, zucchini, eggplant, squash, strawberry.</p>
Bluleaf [14]	<ul style="list-style-type: none"> - Real-time irrigation scheduling. - Weather forecasts. - A personalized daily irrigation schedule for each irrigated plot. - Crop water requirements, soil and irrigation system characteristics. 	<ul style="list-style-type: none"> - Meteorological data - Crop and soil data - Irrigation system data (type of irrigation, flow rate, and pressure of water applied) - Organic matter and effective soil depth - Crop coefficient (Kc) - Reference evapotranspiration (ET_o) 	<p>The application has been tested on durum wheat in Lebanon's Bekaa Valley, a strategic Mediterranean crop.</p>

Table 1. Cont.

Application Name	Services	Input Data	Crop Types
AgSat [15]	<ul style="list-style-type: none"> - Estimate water use and irrigation requirements for several crops at a daily time step. - Provide real-time recommendations for optimizing water use. - Five-day forecast of irrigation requirements. 	<ul style="list-style-type: none"> - Meteorological data—satellite images from Sentinel 2 type of crop, type of irrigation system, and size of irrigation pipe - Evapotranspiration - Basic crop growth coefficient (Kcb) - Kcb is then used to calculate crop water requirements 	<p>Vegetables: carrots, cabbage, aubergines.</p> <p>Fruits: bananas, citrus fruits (such as oranges and lemons), grapes, kiwi, strawberries.</p> <p>Grains: corn, beans.</p> <p>Others: alfalfa (forage plant), almonds (dried fruit).</p>
Smart irrigation apps [16]	<ul style="list-style-type: none"> - Smart irrigation apps assign a mobile application to each type of crop, available on iOS and Android. - Control their irrigation system remotely. - Provide real-time information on irrigation status, as well as graphs and weather data. - Program personalized irrigation schedules to meet the specific needs of their plants and garden. 	<ul style="list-style-type: none"> - Location - Crop type - Soil condition - Current temperature - Number of trees (if requested) - Water flow rate 	<p>Fruits: avocado, blueberry, citrus, peach, pecan, strawberry.</p> <p>Cereals: corn, soybeans.</p> <p>Others: cotton, turf.</p>
PISys [17]	<ul style="list-style-type: none"> - Supply the quantity of water essential for plant growth. - Plan irrigation. - Improve decision making. - Enable real-time monitoring of various variables, such as soil moisture at different depths, meteorological variables, pressure and flow in the main irrigation line, and the status of valves and pumps. 	<ul style="list-style-type: none"> - Meteorological data - Humidity, temperature, wind speed, wind direction, precipitation - Soil and crop characteristics 	<p>Olivier</p>

This literature review shows that two types of applications can be distinguished in our context:

- **Mobile GIS Application:** A Mobile GIS application is specifically designed for use on mobile devices such as smartphones or tablets. It is optimized for a user experience on small touchscreen displays [15]. Mobile GIS applications are typically downloaded and installed on mobile devices from application stores (such as Apple’s App Store or Google Play Store for Android) [16]. They may have features specific to mobility, such as field data collection, real-time GPS navigation, geolocation. Mobile GIS applications often operate in offline mode, but they can also function in both modes simultaneously, referred to as hybrid Mobile GIS applications.
- **Web GIS Application:** A Web GIS app (or web-based GIS application) is a web application accessible via a web browser on any Internet-connected device, whether it be a desktop computer, laptop, tablet, or smartphone. It is designed to be used on screens of various sizes, usually being responsive and automatically adapting to the screen resolution of the device in use [18]. Unlike Mobile GIS applications, Web GIS apps generally do not require installation on the device. Users access them by entering a URL into a web browser. They provide the flexibility to access geospatial data from anywhere with an Internet connection.

Table 2. Critical comparison of existing solutions.

Application	Limits	User Experience
AquaEdge	<ul style="list-style-type: none"> - It only works in the case where the parcel boundaries (drawn by the user) have a homogenous soil type and contain a specific type of crops. - Access request required to use data collected by sensors. - Need access to complete soil data (type, organic matter, plantation density). 	<ul style="list-style-type: none"> - Login required for each use of the application. (–) - Sometimes the application closes oddly when the ‘weather’ button is clicked. (–) - It provides several services, and graphs can be used to visualize all the necessary parameters, i.e., temperature, humidity, evapotranspiration. (+)
Sowater	<ul style="list-style-type: none"> - Difficulty to take into account the variability of the crops themselves. Each crop has specific water requirements at different stages of growth. - Data reliability can be a major limitation as the app relies only on satellite images. 	<ul style="list-style-type: none"> - It calculates the quantity, frequency, and duration of irrigation. (+) - Lack of data visualization either in relation to the crop or to the soil. (–)
Irrismart	<ul style="list-style-type: none"> - It works only when the crop and soil are homogeneous. - It can only be used for drip irrigation. 	<ul style="list-style-type: none"> - It does not give the user the freedom to make the decision. (–) - It gives the quantity of irrigation water directly, without displaying the data on which it is based. (–) - Keeps a history of irrigation records for each plot and each crop. (+) - Requires the user to enter extensive information on soil, crop, and irrigation system. (–)

(–) negative experience; (+) positive experience.

Based on the literature review of existing solutions, only a few applications are designed for arboriculture and offer multiple services simultaneously, which makes irrigation management difficult. This study aims to propose and develop an innovative Web GIS solution named ‘Soqia’ for the dynamic monitoring of the water status of fruit trees, providing farmers with crucial tools for effective irrigation management. The resulting application focuses on an optimal user experience. This Web GIS solution addresses the following two major challenges: spatio-temporal monitoring of trees’ status and the optimal estimation of tree water needs.

The next sections of the article are structured as follows: the description of the application architecture, implementation of the solution, validation, discussion, and conclusion.

2. Material and Methods

Soqia is characterized by serving as a decision-making solution, providing users with real-time and 8-day water irrigation forecasts, along with advanced spatio-temporal tracking of vegetation indices through interactive maps and graphs. Unlike other applications, Soqia uniquely integrates these features, offering users a comprehensive tool for making well-informed and timely decisions regarding the amount of water to irrigate.

2.1. Description of the Application Architecture

The proposed architecture takes into consideration the prerequisites for an optimal management of irrigation in terms of, namely,

- Monitoring the soil and crop hydric status during the whole crop cycle. Real-time monitoring allows for an appropriate estimate of the crop water need and thus an optimal timing for water supply.
- Adjusting water supply to phenological stages.
- Collecting daily weather conditions (temperature, humidity, wind speed, radiation) from the closest metrological station in order to estimate daily evapotranspiration on a daily and weekly basis.

- Using a meteorological database to obtain forecasts using APIs for short-term agricultural activity planning. A three- to seven-day forecast has proven to be the ideal situation farmers are looking for to prevent adverse effects of water stress on crops.
- The estimation of daily crop evapotranspiration. This information is crucial for ensuring adequate irrigation.
- Estimating weekly crop evapotranspiration: Users also require an estimate of weekly crop evapotranspiration to have visibility of irrigation requirements.

The approach adopted for the implementation of the irrigation monitoring solution relies on a mobile application accessible via the web.

Regarding the selection of a web application, it greatly facilitates the distribution and updating of the application. Users can access it through a simple web browser, eliminating the need to install native applications. Furthermore, the web application ensures a consistent experience regardless of the device used, whether it is a smartphone or a tablet, and regardless of the device's operating system (iOS or Android).

A variety of development tools are combined to ensure the smooth functioning of the application. A database was created using Timescale, a time series database [19], and PostGIS, a spatial database extension for PostgreSQL [20], each bringing specific advantages for storing our data. For full-stack development, we used React, a JavaScript library for building user interfaces [21], and Node.js with Express for the backend. Node.js is a runtime environment that allows the execution of JavaScript code server-side. Express is a web application framework for Node.js, simplifying server-side development [22,23].

For PostGIS, the map server used is Geoserver, which allowed the display geospatial data on the base map using the OpenLayers library [24], responsible for displaying interactive maps in web applications. It is used to integrate OpenStreetMap cartographic data into a web application [25].

Various available data sources are used to feed our application. Soil temperature and humidity sensors provide real-time data on local conditions, while Google Earth Engine and the APIs of OpenWeatherMap and WeatherBit supply our application with meteorological and geospatial information [26,27].

The Figure 1 illustrates the technical architecture of the solution proposed as 'Soqia':

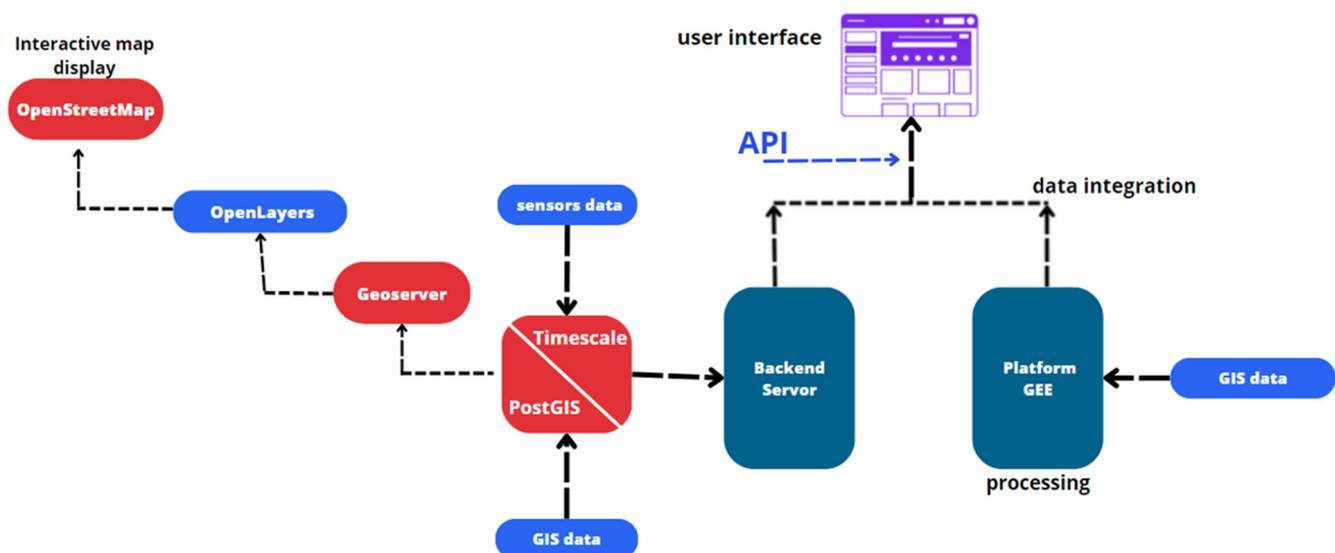


Figure 1. Technical architecture of the application.

Data required to implement the proposed solution include

- Real-time soil temperature;
- Real-time soil humidity;
- Satellite imagery to extract vegetation index data (NDVI, SAVI, EVI, NDMI, and NDWI);
- Geospatial data of the orchard, i.e., the geometries of the orchard components;
- Daily meteorological data (air temperature, air humidity, precipitation, wind speed);
- Weekly weather forecasts for the orchard area;
- Measured evapotranspiration if available;
- Specific crop parameters for estimating water needs (e.g., crop cultural coefficient Kc).

The use case diagram summarizing the functionalities of 'Soqia' application is presented in Figure 2.

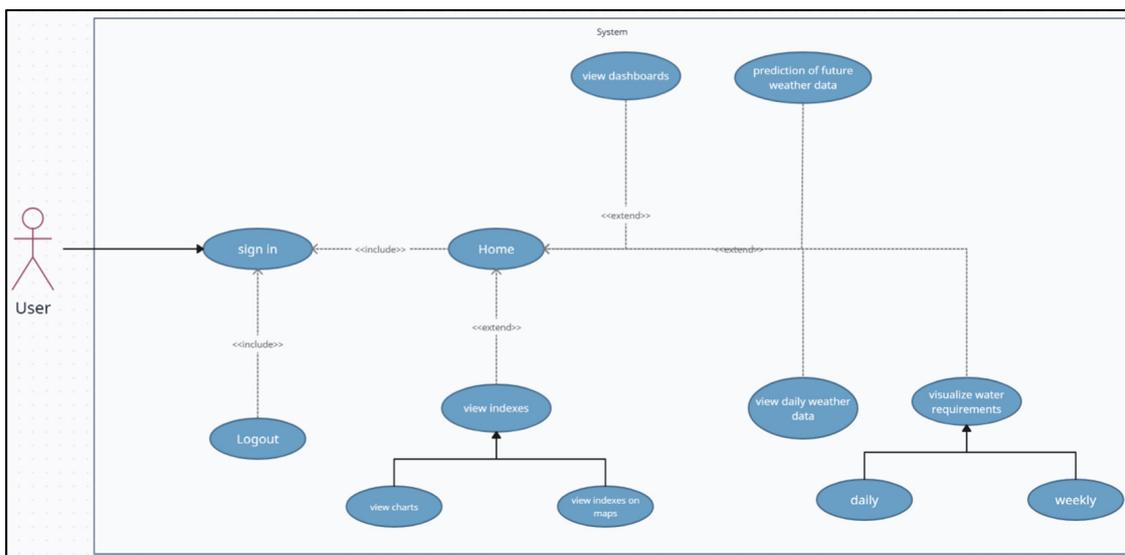


Figure 2. Use case diagram.

The use case diagram illustrates user–system interaction, user types, and their interactions in a system [28]. The interaction with the application begins with authentication, where the user enters their username and password to access the application. Once logged in, the user can navigate between the various services provided by the application. The functionalities include

- The visualization of vegetation index maps;
- The visualization of index evolution charts;
- The visualization of soil parameters;
- Access to current weather data;
- The visualization of weather forecasts;
- The estimation of daily evapotranspiration;
- The visualization of evapotranspiration forecasts;
- The estimation and visualization of tree water requirements.

2.2. Implementation of the Solution Prototype

2.2.1. Presentation of the Study Area

The study area is a farm in the Kasbah of Ait Aammour located in Azrou, north of Morocco (coordinates: Lat = 33°25'02" N, long = 5°17'27" W). The farm covers an area of approximately 10 hectares and consists mainly of apple and pear trees, home to different varieties: Jérémine, Gala, Rienders, Harrow, and Harrow Sweet. The plot is spatially subdivided into four sectors. Figure 3 shows the location and boundaries of the farm.

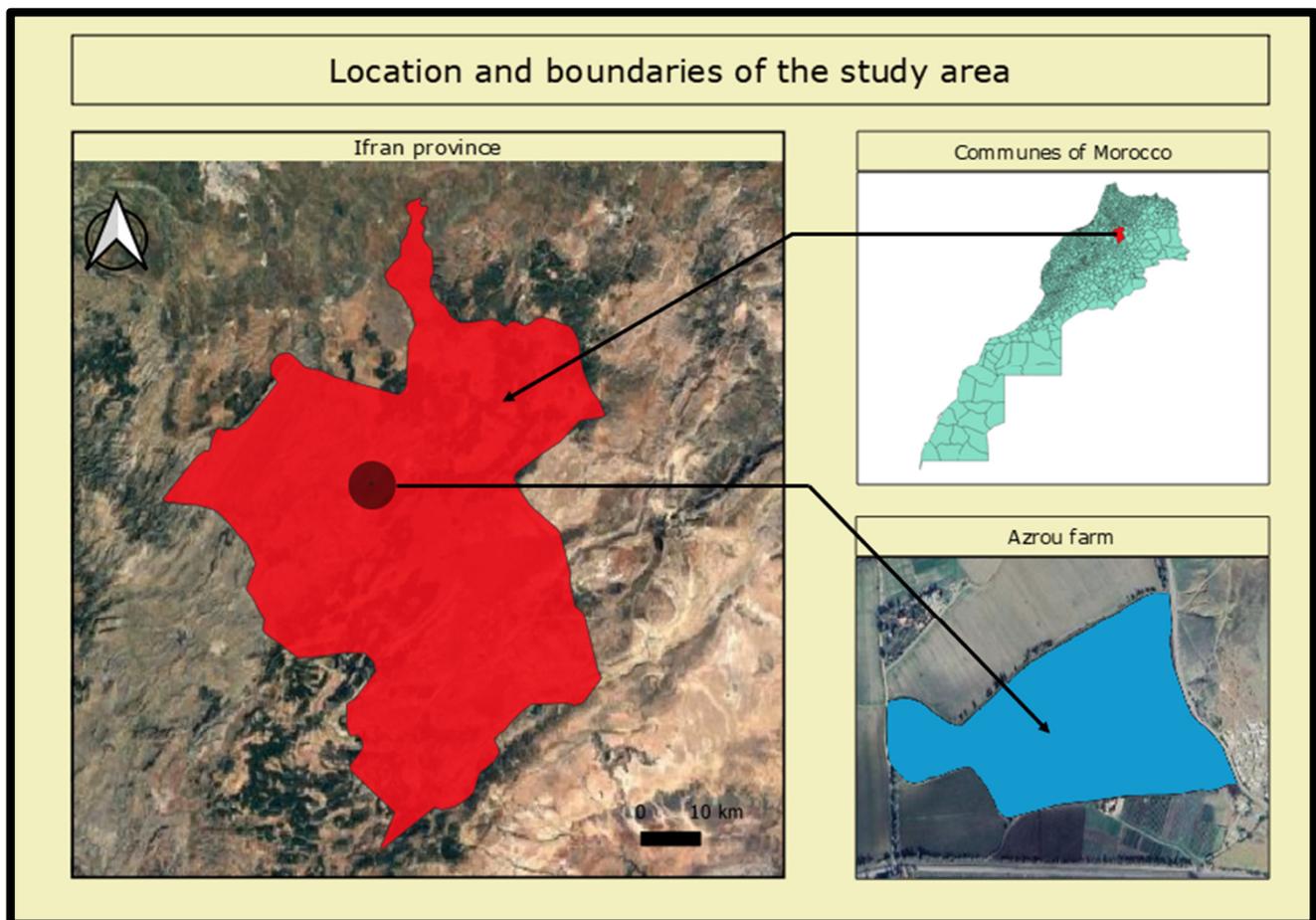


Figure 3. Location and boundaries of the study area.

The farm is divided into two apple blocks, one featuring the Jérôme variety in 26 rows and the other featuring Gala in 26 rows, both with 4 m spacing between successive rows.

There is also a pear block consisting of 22 rows, with a variety planted every 4 rows: Harrow, Harrow Sweet, and HW623. In the first 11 rows, half of them are occupied by another variety, which is Karmine.

At the parcel level, there are two soil temperature and humidity sensors and a weather station:

- One sensor is in the Jérôme variety block of the apple orchard;
- Another sensor is placed in the Gala variety block of the apple orchard;
- The weather station is installed at the head station;
- The following diagram (Figure 4) illustrates the devices installed on the farm and the measurements they collect:

The farm is equipped with a drip irrigation system that uses a well as its main water source. It also has a water storage basin and uses photovoltaic panels to power the pumps and head station.

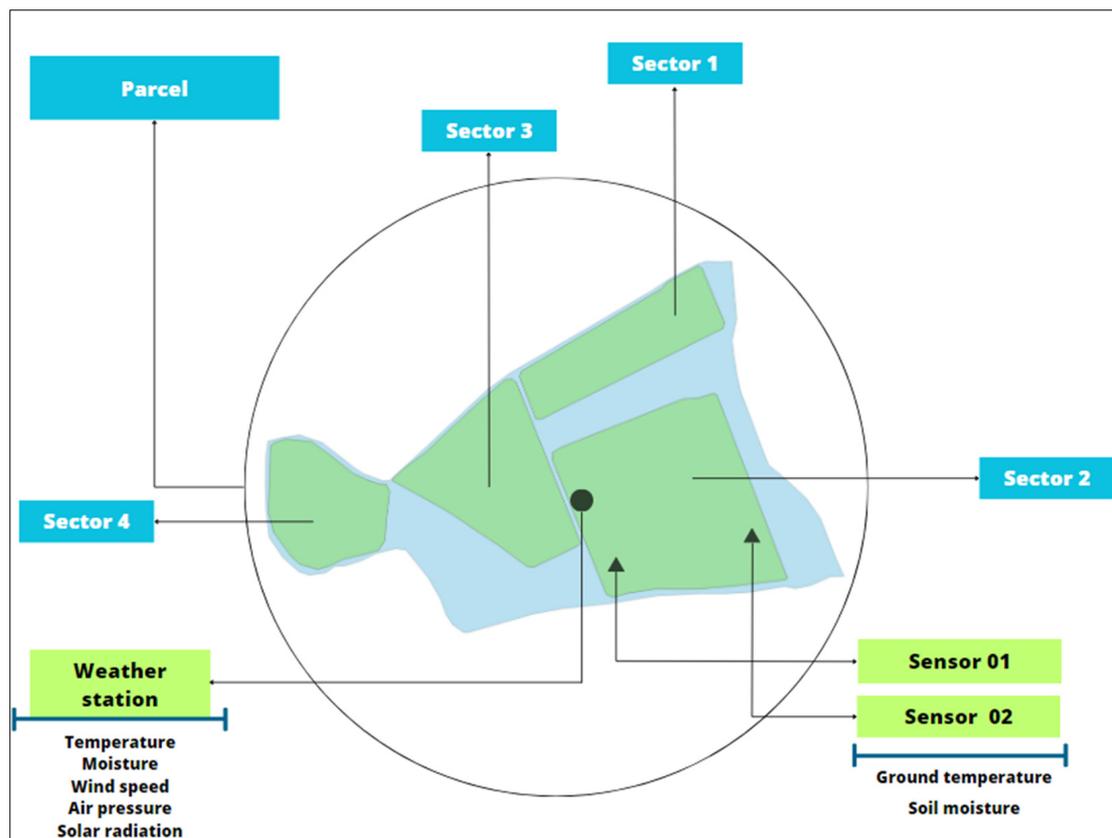


Figure 4. Illustration of the devices installed on the farm.

2.2.2. Data, Databases, Languages, and Platforms Used

Available Data

Regarding the available data for the case study, we initially had ground sensors in place. Two sensors were installed to measure and record soil temperature and humidity every 15 min. Currently, these data are accessible on the farm website. These data serve as test data. A direct connection between the sensors and the database enables displaying the data on the user interface and updating it automatically every 15 min.

A weather station was initially installed to collect data such as air temperature, air humidity, wind speed, solar radiation, and atmospheric pressure. We sought an alternative source of meteorological data, namely, websites offering APIs for various weather services. In our case, we used the platforms “OpenWeatherMap” and “WeatherBit”. We employed several types of APIs, including the current weather conditions’ API, weather forecast API, and evapotranspiration forecast API. For “OpenWeatherMap”, we exclusively utilized free APIs, such as humidity forecasts. Concerning WeatherBit, we utilized the API named “Ag-Weather Forecast API”, providing an 8-day forecast of meteorological data specific to the agricultural industry. Regarding the information provided by the APIs, when using daily data, the measurements are instantaneous. However, when it comes to forecasted data, both weather information and estimated water quantity are projected with a frequency of at least three forecasts per day for the next eight days.

Additionally, we accessed other data sources, notably the Google Earth Engine platform, which houses an extensive cloud-based database containing thousands of satellite images and geospatial data. These images proved to be valuable for extracting vegetation indices for the study area over the required period of time.

Database Design

Design of the logical model or class diagram constitutes the first step in the development process. The logical model helps define key entities, their relationships, and associated attributes, providing a structured and comprehensive view of the system. Creating this model upfront establishes a solid foundation for the future design of the database, facilitating an understanding of interactions between the components. It is truly the cornerstone upon which all subsequent stages of database development rest, underscoring its pivotal role in the effective planning and implementation of any data management system. Figure 5 below shows the class diagram for the databases. This diagram depicts the farm entities and their associated relationships and attributes. Its creation was made possible using StarUML software version 5.1.0:

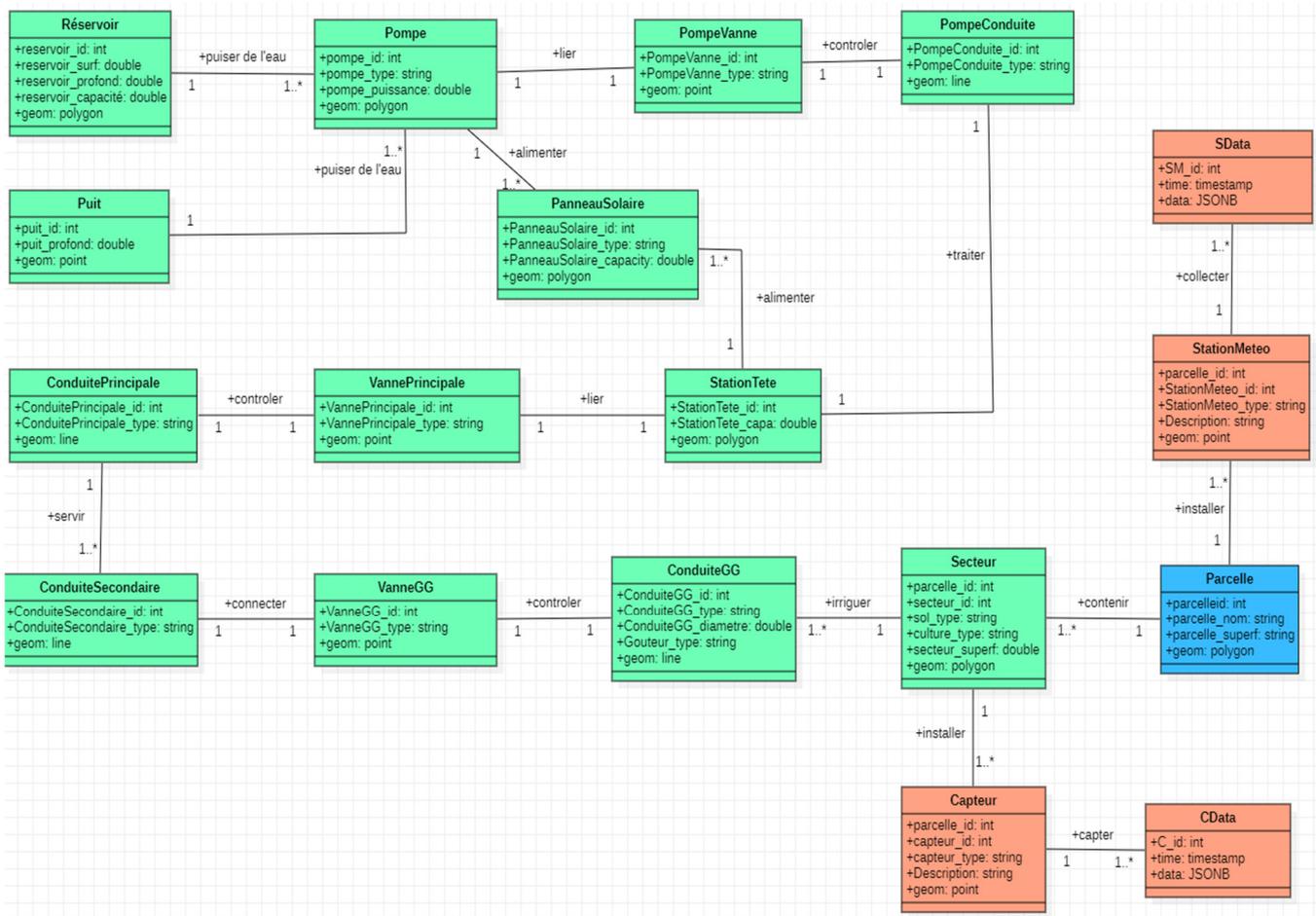


Figure 5. Class diagram of our databases (the symbol ‘1..*’ represents a multiplicity where there is at least one instance of the associated class, but there may be several).

Each class in the diagram corresponds to a distinct entity within the farm. The hypertables added to the Timescale database are as follows: C_Data and S_Data. The first represents the hypertable of data collected by each sensor, while the second symbolizes data recorded by the weather station. The remaining classes are stored in another database, namely, PostGIS.

In the context of the spatio-temporal tracking application for arboriculture, we employed Timescale to store real-time sensor data. This Time-Series Database (TSDB) is an optimal choice for various reasons, including relational capabilities, high performance, scalability, data compression, and compatibility [29].

The central principle of TimescaleDB is based on hypertables, which are singular tables providing a simplified view for users. In practical terms, hypertables serve as a virtual representation of multiple individual tables, with each table containing sets of data known as “chunks.” Hypertables can be one-dimensional or two-dimensional and are capable of aggregating data based on time intervals or “partition key” values [29].

We also opted to use PostGIS to store entities with the “geometry” attribute, which encompasses location and boundary information. This allowed us to represent real-world objects as points, lines, or polygons in our database, introducing a spatial dimension to our data. PostGIS is an extension of the PostgreSQL database that expands its support to geographic and geospatial data, enabling us to store, query, and manipulate entities associated with geographical positions [24].

The approach involved stores geospatial data in PostGIS, creating temporary data with QGIS, importing it into PostGIS, publishing it online using GeoServer, and displaying it on the collaborative OpenStreetMap (OSM) using the OpenLayers library. This method enriched the spatio-temporal orchard tracking application by adding an essential geospatial dimension, providing users with an interactive experience.

The logic of displaying geospatial data on a base map is illustrated in Figure 6:

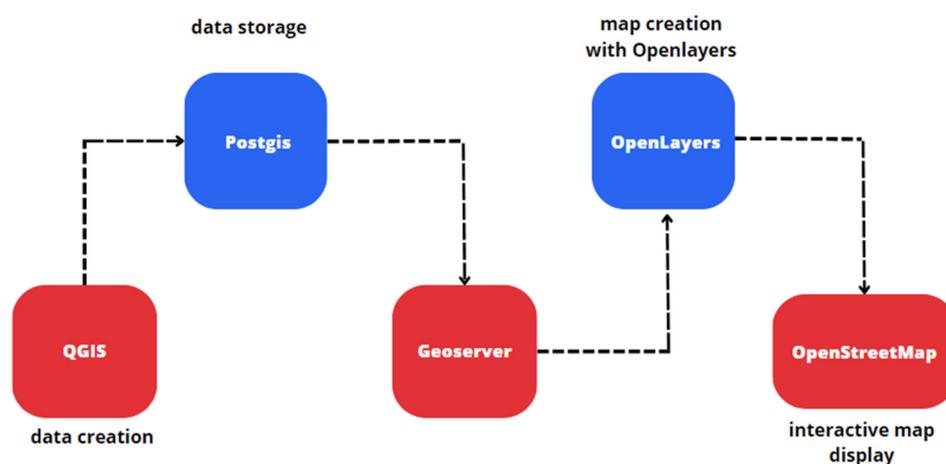


Figure 6. Overlaying geospatial data on an OpenLayers map.

Platforms and Development Languages Used

Development platforms and languages used include the Google Earth Engine platform, React and JavaScript library for building user interfaces, and Node.js with Express for the backend. Visual Studio Code was used as a primary development environment.

2.2.3. Key Steps

The implementation process was divided into several essential steps summarized in Figure 7:

Here is an overview of these key steps:

- **Creation of Data with QGIS:** The process began with the manual creation of provisional data using QGIS, representing spatial entities such as plots, sectors, and pumps. These data served as a foundation for testing our solution and defining the spatial entities to be visualized later on in the map;
- **Integration of Data into Respective Databases:** The generated data were integrated into the appropriate databases. Data from soil temperature and humidity sensors were stored in TimescaleDB, while spatial entities with geometric attributes were stored in PostGIS, providing management and querying capabilities for spatial data;

- **Use of a Hybrid Database:** We adopted a hybrid approach using TimescaleDB as an extension of PostgreSQL to manage sensor data. This combination offered the flexibility of JSONB storage for unstructured data while maintaining the power of SQL for structured data management;
- **Server Connection to Databases:** A robust connection between servers and databases was established to ensure real-time data retrieval. GeoServer was paired with PostGIS to broadcast spatial entities on the map, while Node.js was used to connect to TimescaleDB and manage environmental data;
- **Testing of GIS-related Code with OpenStreetMap and GeoServer:** We evaluated the Geographic Information System (GIS) part using OpenStreetMap as the map base and integrating spatial entities stored in GeoServer. This approach resulted in an interactive map displaying selected elements;
- **Calculation and Visualization of Vegetation Indices with Google Earth Engine:** We used Google Earth Engine, a cloud-based platform for a planetary-scale environmental data analysis and geospatial processing [30], to generate classification maps and charts representing orchard health by calculating various vegetation indices. This included importing data, processing satellite images, calculating indices, and visualizing them on maps. Here is a diagram (Figure 8) illustrating the main steps, all performed in the Earth Engine Code Editor platform:

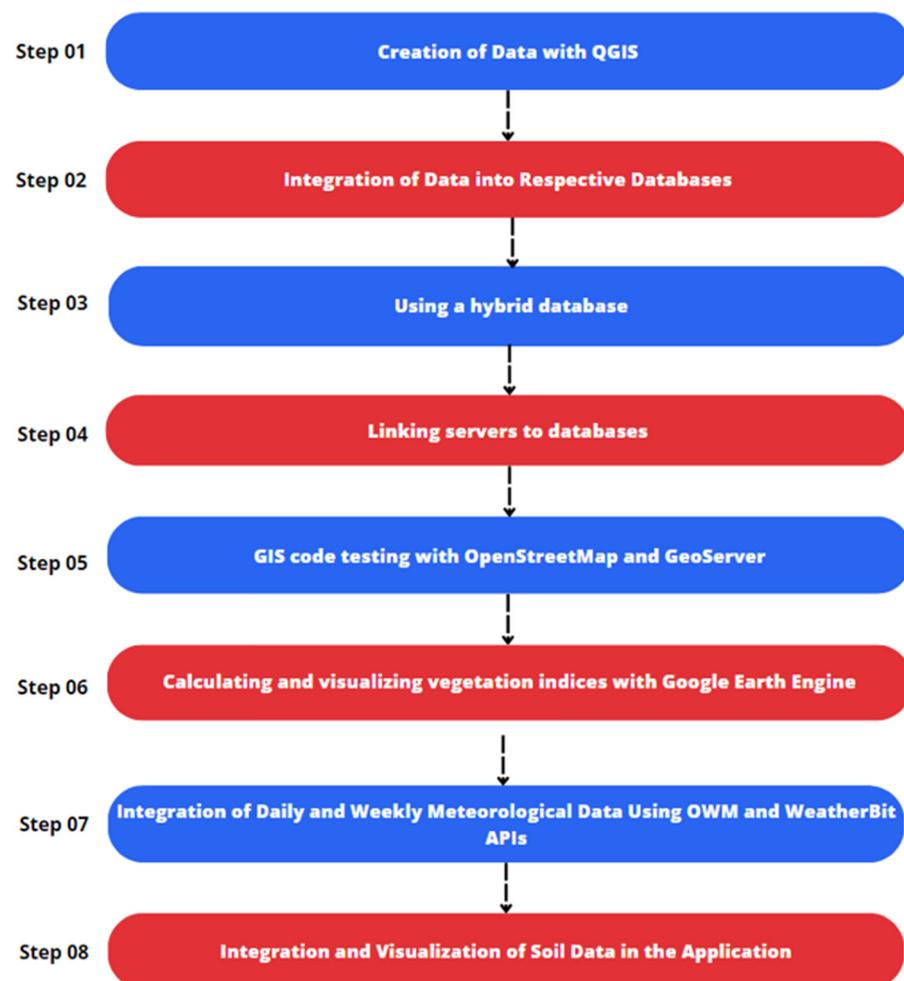


Figure 7. Key stages of implementation.

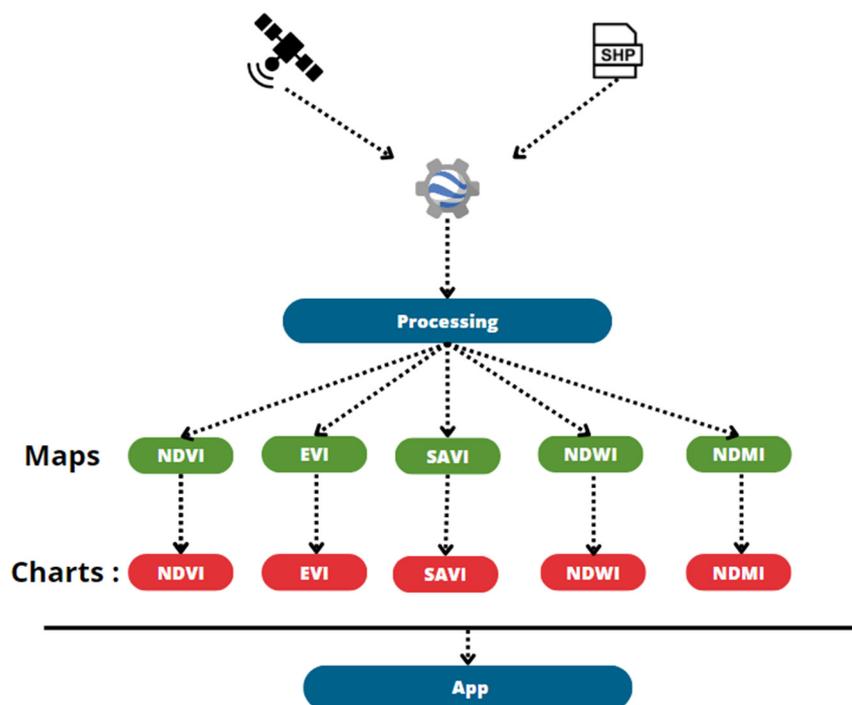


Figure 8. Main steps for creating vegetation index maps and graphs.

In Table 3, the definitions and the mathematical formula of these indices are presented. In addition, this table highlights how each index can assist farmers in optimizing the water used in irrigation:

Table 3. Overview of vegetation indices provided by Soqia.

Index	Definition	Equation	Reference
NDVI (Normalized Difference Vegetation Index)	NDVI is used to determine the health of vegetation by indicating the chlorophyll content of plants. In agriculture, this vegetation index is used to measure the rate of plant cover and the vigor of the crop present on an agricultural plot.	$(NIR - Red) / (NIR + Red)$	[31]
SAVI (Soil-Adjusted Vegetation Index)	SAVI is an adjusted form of NDVI, designed to minimize the influence of soil luminosity by means of a soil luminosity correction factor. This index is often used in arid regions with low vegetation cover.	$((NIR - Red) / (NIR + Red + L)) \times (1 + L)$	[32]
EVI (Enhanced Vegetation Index)	This enhanced index accounts for atmospheric variations and vegetation cover, providing better sensitivity to changes in vegetation cover compared to NDVI. It is more sensitive in areas with dense vegetation.	$2.5 \times ((NIR - Red) / (NIR + 6 \times Red - 7.5 \times Blue + 1))$	[33]
NDWI (Normalized Difference Water Index)	NDWI is an index strongly related to the water content of the plant. It helps create water stress maps and is therefore relevant in precise irrigation management.	$(Green - NIR) / (Green + NIR)$	[34]
NDMI (Normalized Difference Moisture Index)	NDMI indicates the water stress level. It is used to assess and monitor the moisture content of vegetation, helping in irrigation monitoring.	$(NIR - SWIR) / (NIR + SWIR)$	[35]

The parameters used in formulas presented in Table 3 correspond to the following. NIR: Near-Infrared band, Red: Red band, Blue: Blue band, SWIR: Shortwave infrared band, Green: Green band, L: The amount of green vegetation cover (generally $L = 0.5$).

These vegetation indices can be used by the farmer to optimize the quantity of water use for irrigation by visualizing and analyzing graphs and maps of these indices provided by Soqia. NDVI, SAVI, and EVI can help evaluate the health, vigor, and density of vegetation. By monitoring these indices over time, the farmer can identify areas where vegetation is stressed or sparse, indicating potential water needs. NDWI can be used to monitor the plant water content and detect the presence of water in soils or low-lying areas where water may accumulate, thus helping optimize irrigation by avoiding areas with a high value of soil moisture. NDMI can help evaluate moisture content, enabling the farmer to identify areas requiring additional irrigation.

- Integration of Daily and Weekly Meteorological Data Using OWM and WeatherBit APIs: Meteorological data were extracted from the OpenWeatherMap and WeatherBit platforms using their respective APIs. The APIs define how software components should interact, facilitating communication and integration between systems [36]. They were integrated into the front-end of the application, customizing how meteorological data are displayed. APIs provide us with information about weather conditions and other parameters, from which we calculate evapotranspiration, which is influenced by weather conditions, like solar radiation, air temperature, humidity, and wind speed, and varies with the crop type, variety, and development stage, even under similar environmental conditions due to specific characteristics [37];
- Integration and Visualization of Soil Data in the Application: The data stored in TimescaleDB were accessible via a REST API, enabling communication between the front-end (built in React) and the backend (built in Node.js). The Single-Page Application (SPA), a web app that loads a single HTML page and updates dynamically for a seamless experience [38], was utilized to display and visualize data on the user interface, providing an interactive and smooth user experience;
- The following diagram (Figure 9) outlines the steps of Client-Side Rendering, a web development approach where the browser processes and renders content, reducing server involvement [39], (CSR: React in our case) to communicate with the server and visualize data (taking the example of the URL 'localhost/Sensor01', corresponding to the visualization of soil data from sensor n° 01):

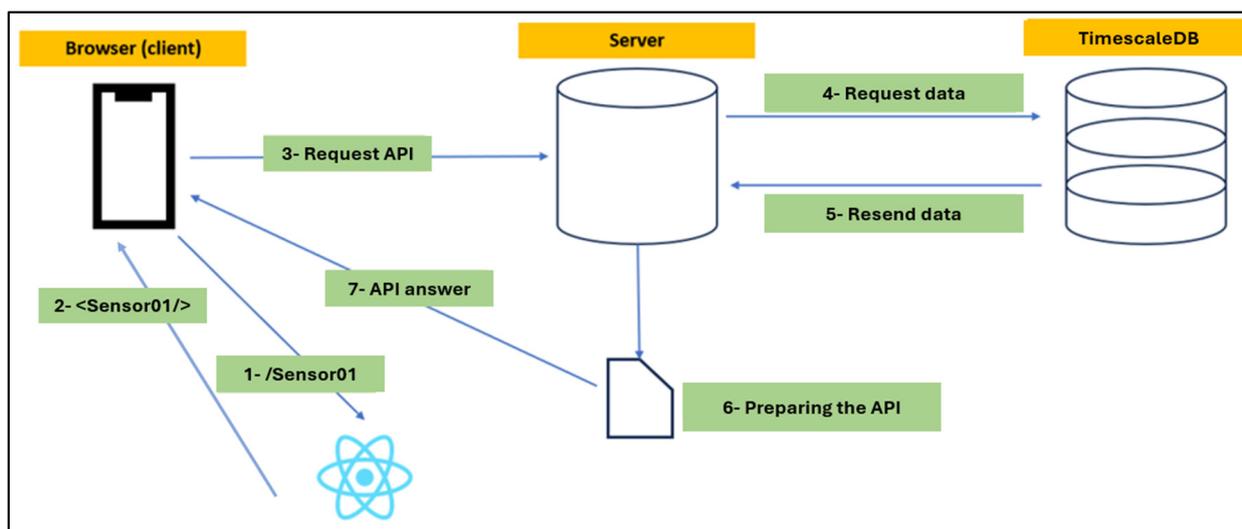


Figure 9. Steps for visualizing data stored in TimescaleDB (sensor example n° 01).

3. Results and Validation

In this section, we will delve into each aspect of the application developed, from the initial access point to the detailed visualization of agricultural data. The application's user manual can be found in Appendix A.

1. Access Page (Figure 10a): This segment focuses on the access page of the application, emphasizing its crucial role in user interaction. Users input their credentials (username and password) to gain entry to the application. Upon successful authentication, they are directed to the home page; otherwise, an error message is displayed.

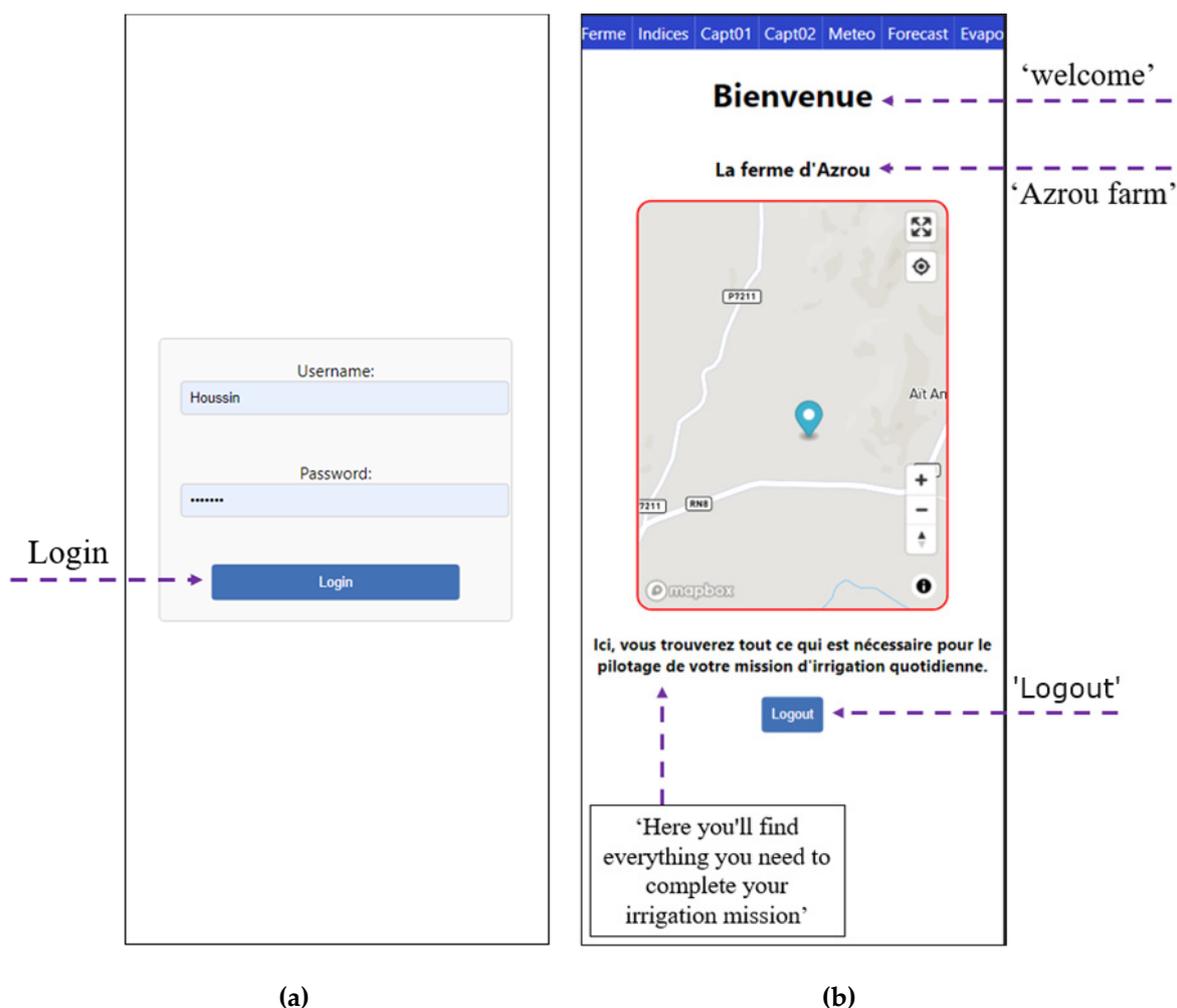


Figure 10. (a) Access page; (b) home page.

2. Home page (Figure 10b): The home page is defined as the users' initial impression. It showcases a map centered on the farm, a marker for the centroid, and a navigation bar to access various functionalities.
3. Service n° 1 (Figures 11 and 12): Spatio-Temporal Monitoring of Vegetation Indices. This section focuses on visualizing classification maps of vegetation indices such as NDVI, SAVI, EVI, NDMI, and NDWI, along with their temporal evolution graphs. The user selects a date between July 1st and November 1st to display corresponding maps, classified into three palettes reflecting the level of index activity in a given area. Interactive tools like DateSlider and the Layers menu facilitate navigation and exploration.

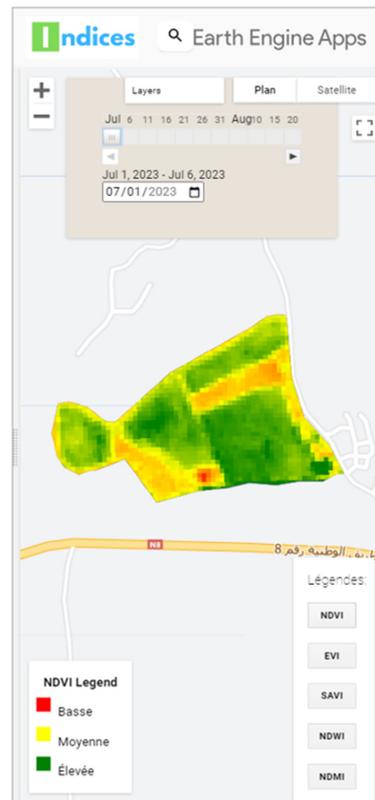


Figure 11. Interface for vegetation index classification maps (Green: high value, Yellow: medium value, Red: low value).

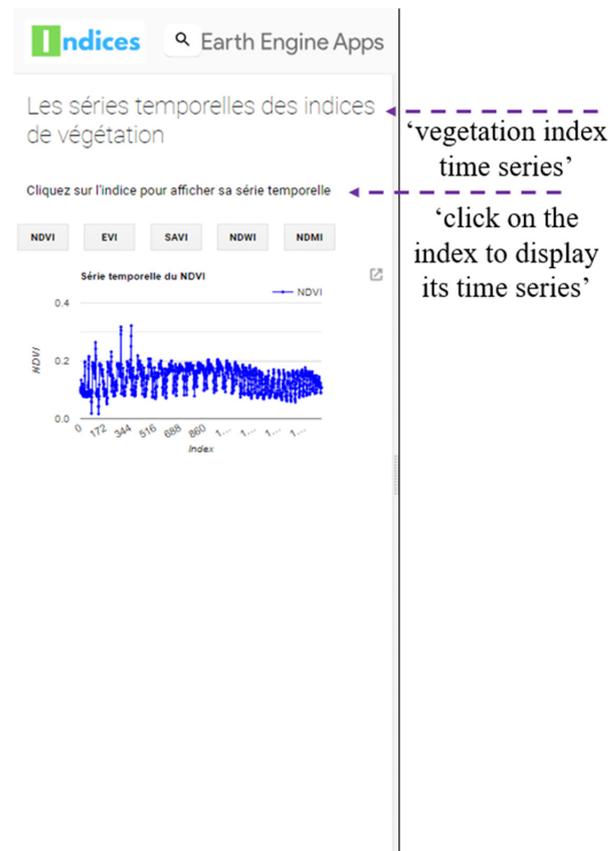


Figure 12. Vegetation index time series.

- Service n° 2: Dashboards for sensor data (Figure 13). This section looks at the detailed dashboards for data collected by the JEROMINE and GALA sensors. Temperature and soil moisture graphs display variations over the past 24 h, with a recording frequency of 15 min. Interactive bars provide a user-friendly representation of values and allow points to be selected for precise information.

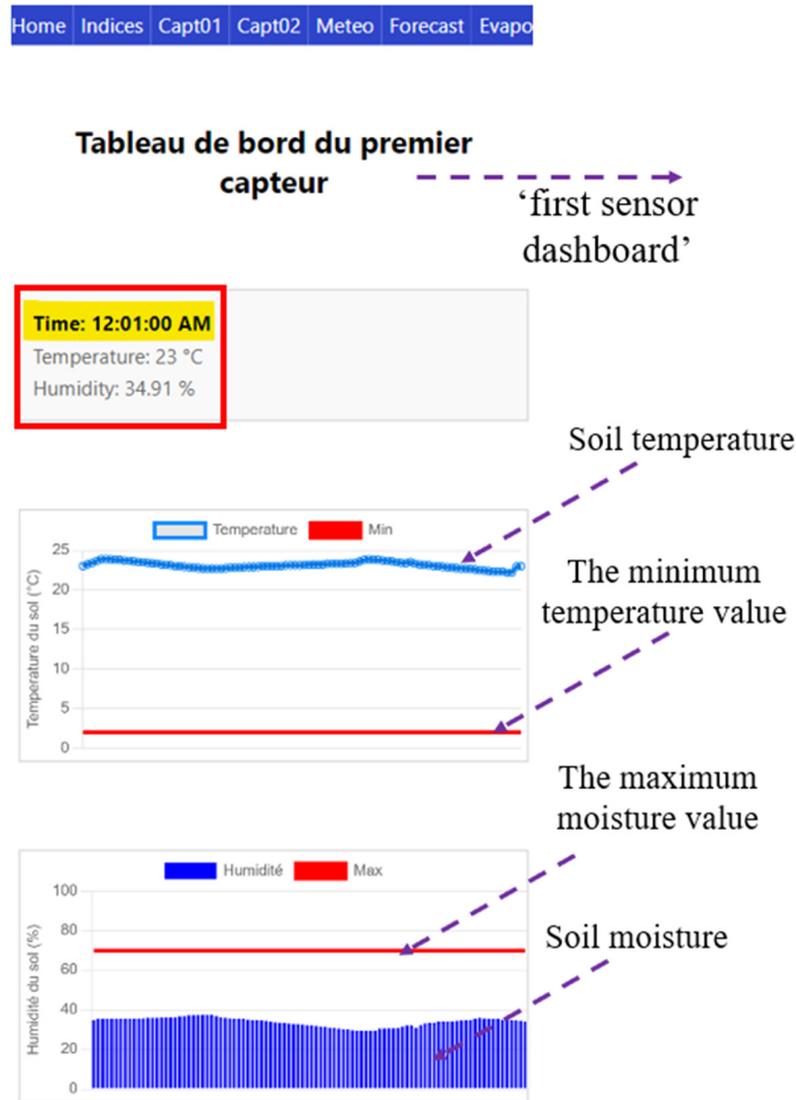


Figure 13. Dashboard screen for sensor 1. The red box at the top left indicates that clicking on the graph allows users to view the exact time of recording and the corresponding values for soil temperature and moisture.

- Service n° 3: Current Weather Conditions Consultation (Figure 14). This section explains how users can access current weather conditions. A MapBox map displays the plot boundaries with meteorological information, including air temperature, air humidity, wind speed. These data empower farmers to make informed decisions for their agricultural activities.

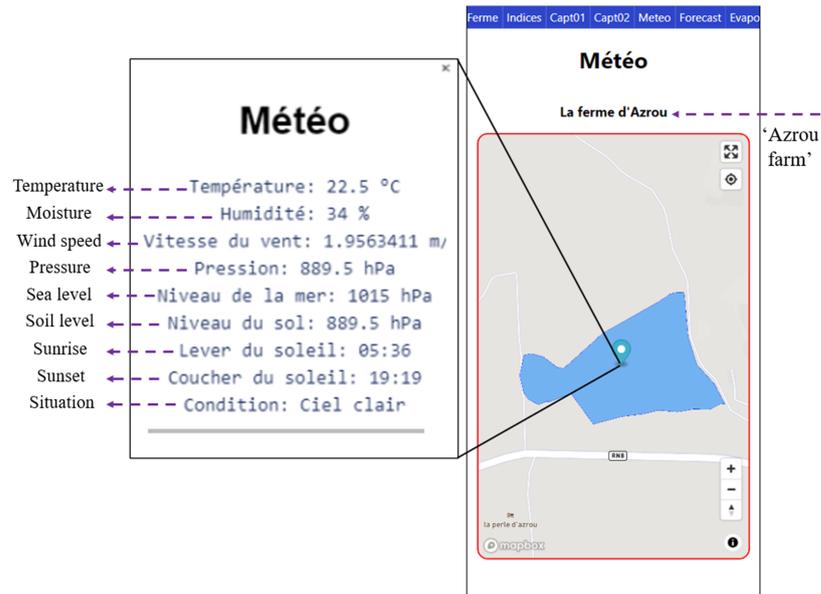


Figure 14. Weather Conditions Consultation.

- Service n° 4: Visualization of Downloaded Weather Forecast Data (Figures 15–17). This service provides farmers with comprehensive forecasts of future weather conditions for the next 8 days. The data include air temperature, air humidity, wind speed. Clear and interactive graphs enable users to review the values of each variable and adjust their irrigation schemes accordingly. It is important to note that the forecasting of meteorological data comes from available APIs, namely, WeatherBit and OpenWeatherMap. Each website employs a combination of numerical weather prediction models to generate these forecasts such as GFS, and ECMWF [40].

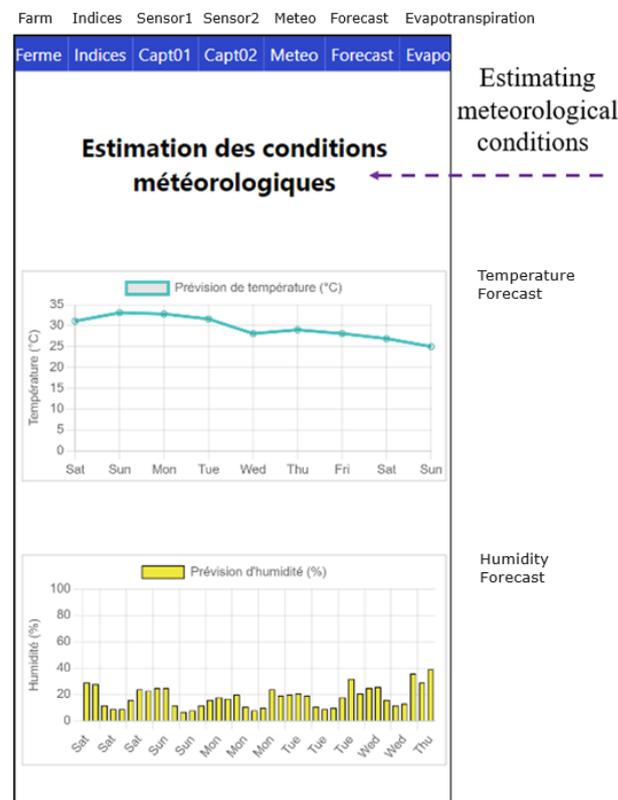


Figure 15. Page 1 of the service screen 4 (Weather Forecast: Temperature and Humidity).

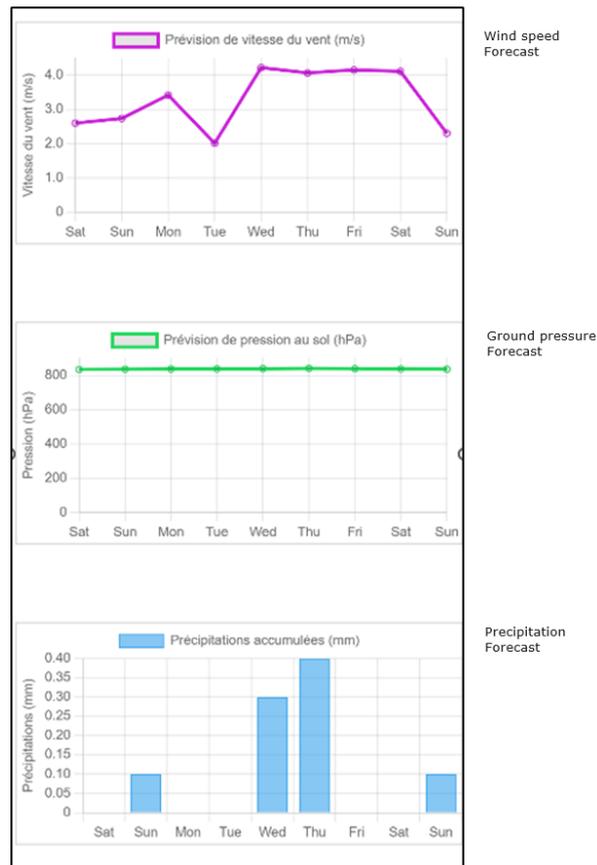


Figure 16. Page 2 of the service screen 4 (Weather Forecast: Wind speed, Ground pressure and Precipitation).

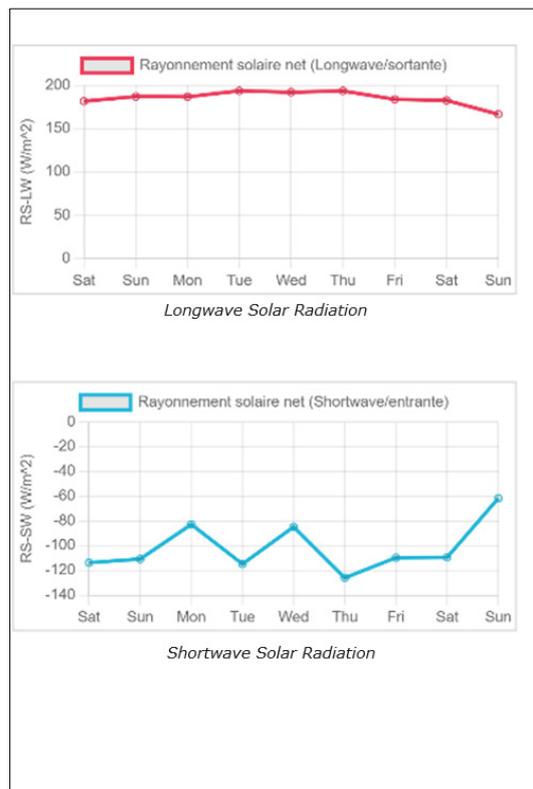


Figure 17. Page 3 of the service screen 4 (Weather Forecast: Solar Radiation).

- Service n° 5: Visualization of Downloaded Evapotranspiration Forecasts (Figure 18). This section illustrates how the application visualizes daily and weekly forecasts of reference and crop evapotranspiration. These data are crucial for optimal irrigation. Farmers can plan water quantities based on weekly forecasts and adjust their irrigation schemes accordingly.



Figure 18. Service screen 5 (Evapotranspiration estimation).

- Service n° 6: Visualization of Geospatial Data on OpenStreetMap (Figure 19). This service enables users to explore the geographical entities of the farm by integrating stored information with OpenStreetMap mapping. Users can precisely select the specific entity they wish to examine. It is important to note that the results of this phase have not been integrated into the final application due to constraints related to the quality of geospatial data.

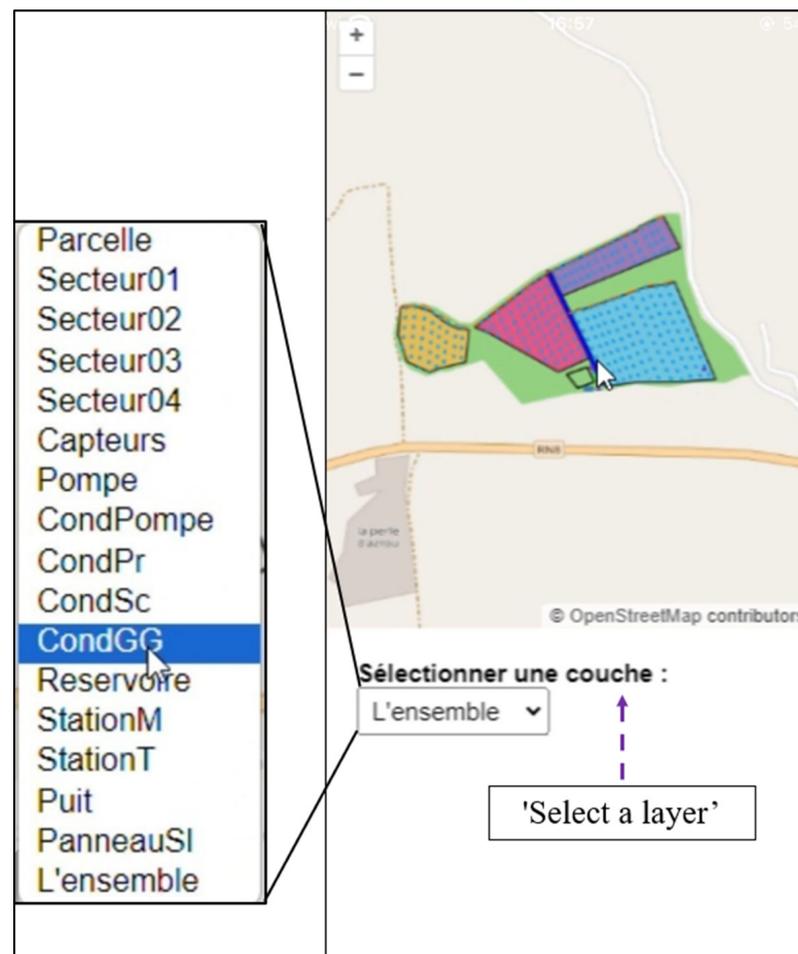


Figure 19. Farm component mapping interface.

4. Discussion

The main objective of 'Soqia', the SIG-Web solution developed in this study, was to meet the specific needs of farmers for irrigation management and decision making based on weather and agronomic data. In light of the needs defined by users at the beginning and thereafter, how services are provided by the application effectively meets these needs:

- Track the soil water status during the crop growing period: The soil parameter visualization service, including temperature and humidity, provides farmers with the ability to monitor these parameters in real-time and take relevant actions. The data recorded in the database are transmitted in real-time from the sensor to the database.
- Diagnose fruit growth phases in orchards: Visualization services for vegetation indices' classification maps and indices' evolution graphs meet this need. Farmers can assess the condition of trees in different parts of the orchard and track seasonal changes to assess the crop status, density, and growth.
- View daily weather conditions: The current weather data viewing service provides farmers with real-time access to crucial weather information for planning agricultural activities.
- Visualize forecast weather data: The service for displaying weather forecasts over a period of 7 days meets this need by providing reliable data to anticipate short-term weather conditions and allow optimal irrigation scheduling.

- Estimate the daily crop evapotranspiration: The daily evapotranspiration display service provides farmers with estimates of the water requirements of the trees, which is also essential for optimal irrigation scheduling.
- Estimate weekly crop evapotranspiration (forecasts): The weekly crop evapotranspiration forecast visualization service allows farmers to plan water distribution strategically for each week.

In light of the services provided by the solution in relation to the needs we have defined in collaboration with users, it is clear that the solution responds effectively and relevantly to the needs of farmers. Each service has been carefully designed and tested to specifically target identified needs. The solution provides tailored tools to support irrigation planning and decision making. These innovative tools bring significant value to the developed solution compared to platforms previously tested. However, it should be noted that there are external data used, such as the installed farm sensors' data and the weather station data. The services rely on accurate and continuous data, which directly impact the quality of the information and services available for users.

One of the key features that gives distinctive value to the developed solution is its ability to provide evapotranspiration forecasts as well as detailed weather data. This element is a real support in the field, given that the majority of similar platforms focus on real-time monitoring rather than prediction. Another added value that distinguishes the solution is its ability to offer rich and informative visualization in the form of classification maps and graphs for different periods. This functionality provides tremendous value because it addresses a unique and often overlooked need of farmers in the field. Unlike most solutions available on the market, which mainly focus on presenting dashboards, the developed solution provides a visual representation of the spatio-temporal distribution of vegetation indices.

'Soqia' is a SIG-Web solution developed in cooperation with farmers and professionals to provide irrigation support for arboriculture, taking into account the actual needs, and offers relevant information for users presented in a simple understandable form. The solution needs information of the farm equipment and data from field sensors and a meteorological station to run. The more information is accurate, the more reliable the outputs will be. To evaluate its performance, 'Soqia' was implemented and tested on a demonstrative case study. The results are very encouraging. More tests are undergoing to assess the performance in large areas.

The solution was developed using accessible and flexible environment tools. It is a result of a partnership between the research community and professionals. The services were developed based on irrigation advisors and farmers' needs and suggestions to meet their irrigation scheduling. More tests and developments are needed to overcome current limitations and to estimate recommendations more aligned with irrigation water management requirements.

The GIS-WEB solution for spatio-temporal monitoring remains of paramount importance in irrigation, given its advantages and its ability to support farmers in improving their yields, while reducing the consumption of water necessary for irrigation. This solution plays a central role in the evolution toward more intelligent, sustainable, and efficient agricultural management. 'Soqia' offers various services and has several characteristics. However, it remains unfinished. More attention in the future developments must tackle more options for expanding data collection capabilities, as well as the management of the components of the farm. The GIS components need improvements to integrate drone imagery and explore the capabilities of artificial intelligence for a more spatial and predictive analysis and thereby contributing to sustainable agricultural production.

5. Conclusions

This study proposes a promising solution for irrigation monitoring, enabling farmers and orchard managers to make informed decisions regarding irrigation and crop management. This work aimed to improve the management of fruit tree orchards by developing a responsive GIS-WEB solution for spatio-temporal irrigation monitoring. The state of the art reveals the growing importance of spatio-temporal orchard monitoring solutions and associated technologies. The developed solution, 'Soqia', provides support to farmers based on the field status, daily and weekly evapotranspiration estimations, as well as daily and weekly weather data. The solution also offers a rich and informative visualization of the soil and trees' status in the form of classification maps and graphs for different periods as well as a visual representation of the spatial-temporal distribution of vegetation indices. Time series vegetation indices' maps and graphs are calculated based on multispectral satellite images. The contribution of the Soqia solution to improve the management of irrigation at the orchard level fits perfectly with the objectives of the national agricultural development strategy, which aims, among other things, at the promotion of digital technologies for the improvement in farmers' working conditions, the increase in farms' profitability, and the rationalizing of the use of water resources in a context of climate change. The solution is continuously improved based on users' experience and recommendations. Aspects of improvements include more data collection capabilities, the extension of options related to the management of the components of the farm, drone images' integration, advanced forecast capabilities and a spatial analysis using machine learning techniques, and the addition of the 'notifications' feature to the application to keep the user informed of any updates. In addition, we suggest considering the integration of dendrometers alongside the currently emphasized tensiometers. This would broaden the range of compatible sensors and extend the application's utility, particularly in the context of arboriculture. Additionally, we recommend a further exploration of the correlation between evapotranspiration and soil water percolation. Recognizing the pivotal role of this relationship in water management for arboriculture, delving deeper into these connections, will contribute to a more comprehensive and effective solution in future developments.

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Data Availability Statement: Data are included in the article; further inquiries can be directed to the corresponding author.

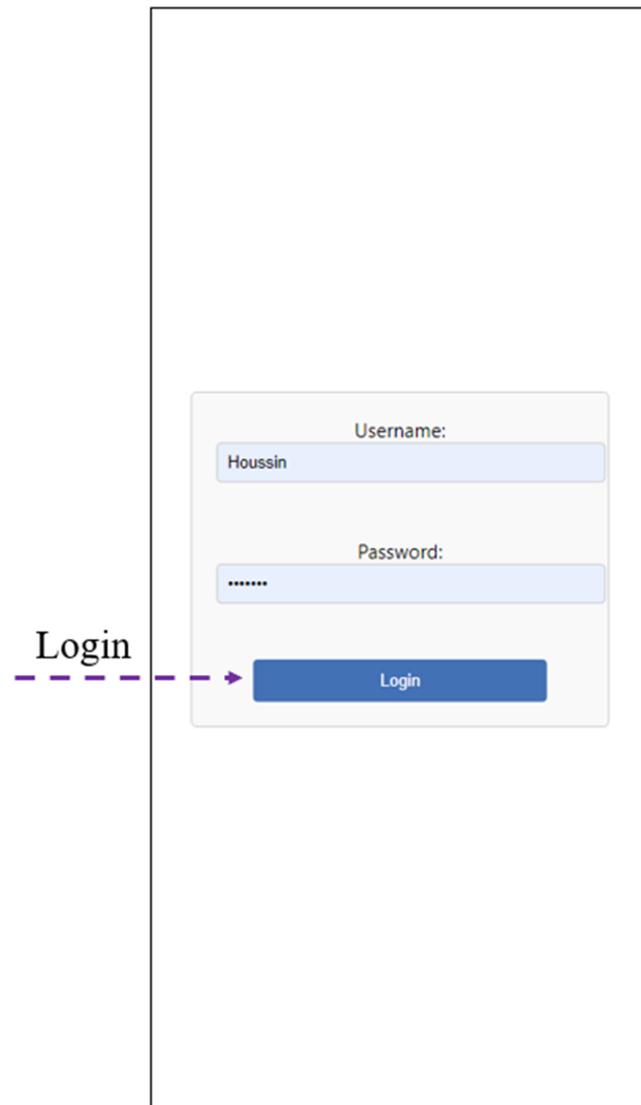
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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

This guide comprehensively explains the steps for connecting and using the application, accompanied by subtitles to facilitate a clearer understanding of each topic.

- Login: To log in, simply enter the username and password.



The image shows a login form with the following elements:

- A label "Username:" above a text input field containing "Houssin".
- A label "Password:" above a password input field containing ".....".
- A blue button labeled "Login" below the password field.
- A dashed purple arrow labeled "Login" pointing to the "Login" button.

Figure A1. Access page.

As illustrated in the above figure, this initial interface serves as the entry point for our application. It is the login page where users need to provide their credentials, namely, their username and password. If the data are valid, access is granted directly to the home page. Otherwise, an error message appears on the screen, indicating that either the password, the username, or both are incorrect.

- Navigate the application: Once you have logged in, you can navigate through the various application windows and consult all the services on offer. To view information about the farm or the daily weather forecast, simply click on the 'location' icon, and the text window (containing the information) will appear. For other services, on the other hand, the information is displayed directly as soon as you click on the service in question.



Figure A2. Home page.

In the above figure, the home page features a 'MapBox' map centered on our farm. At the center of this map, a marker symbolizes the centroid of the farm. A simple click on this marker triggers the automatic display of a pop-up window containing general information about the orchard, such as coordinates, area, and types of crops. At the bottom of the page, brief text is accompanied by a "Logout" button to exit the application.

At the top of the interface, a horizontal bar allows navigation between the various screens of the application. Each screen in this bar offers a specific functionality.

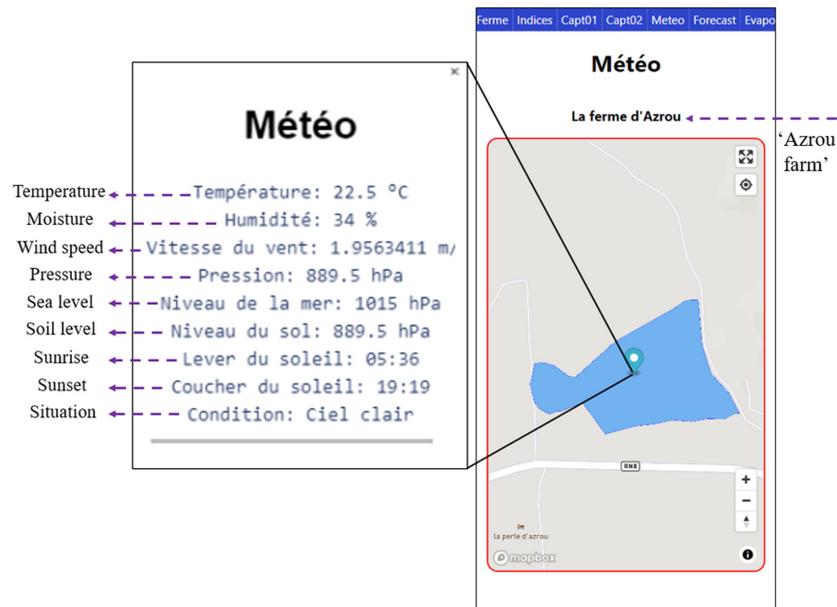


Figure A3. Weather consultation.

In the center of this page, a MapBox map is displayed, overlaid with a geojson file illustrating the parcel boundaries in the form of a blue polygon. The polygon is centered by a marker. By clicking on this marker, a pop-up window appears, displaying the day’s meteorological information: air temperature, air humidity, wind speed, atmospheric pressure at sea level and on the ground, sunrise and sunset times, as well as the climatic situation (sunny, clear skies, clouds, etc.).

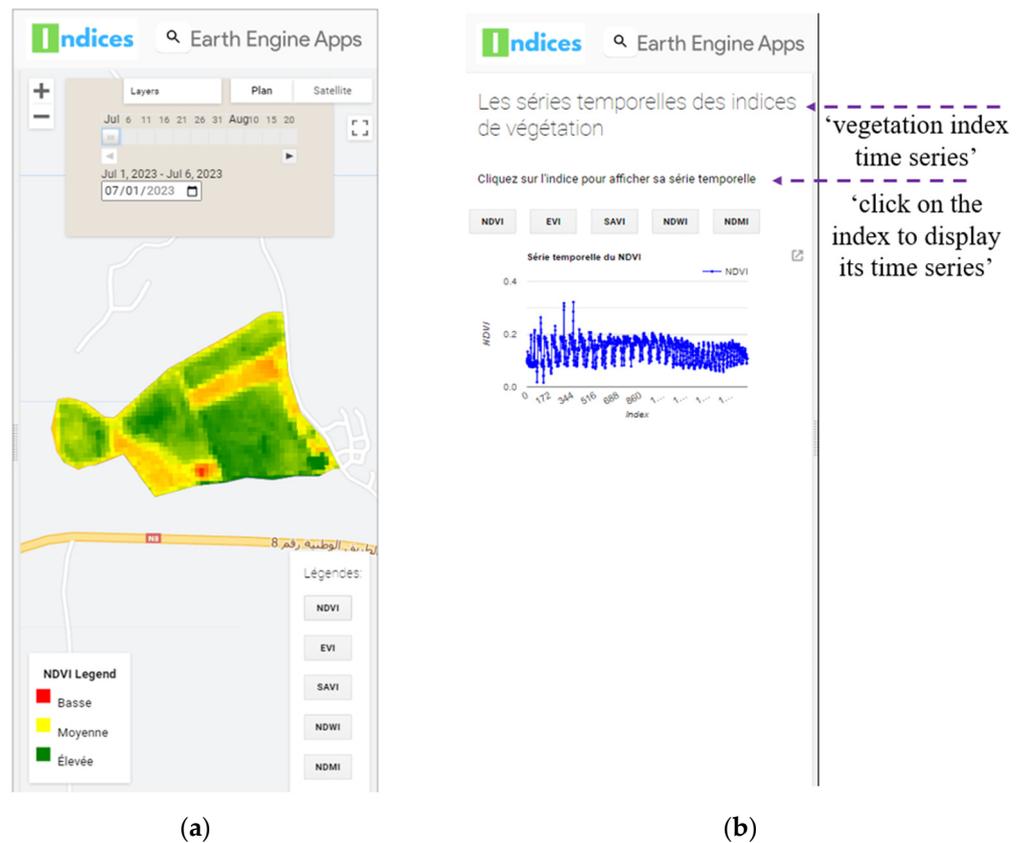


Figure A4. (a) Interface for vegetation index classification maps; (b) index graph interface.

This section presents the visualization of vegetation index classification maps and evolution graphs for an in-depth understanding of these indices over time. Using the “DateSlider” tool and once the date has been selected, the corresponding index cards will be displayed automatically.

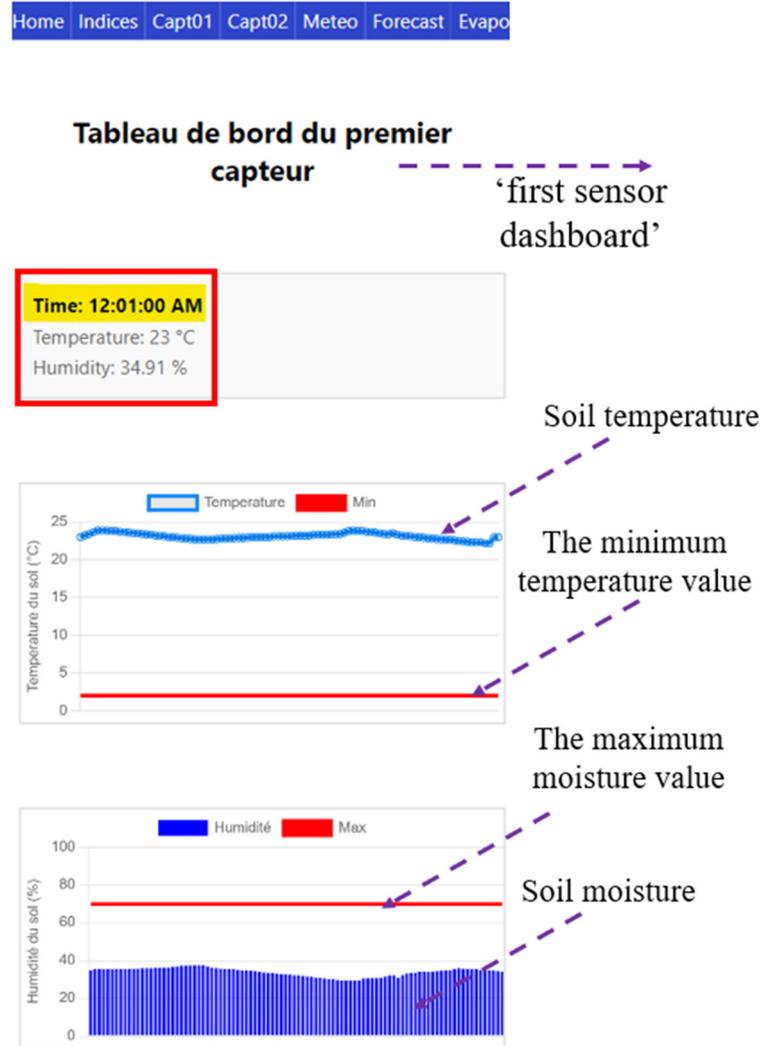


Figure A5. Dashboard screen (sensor 1).

As illustrated in the figure above, on the “Capt01” screen dedicated to “sensor n° 1”, the user can access real-time data collected by the sensor installed in the “JEREMINE” apple orchard. Temperature and soil humidity graphs clearly display variations over the past 24 h, given the frequency of recording every 15 min. The user can examine all 96 recent data points for each parameter. In addition, an interactive bar (indicated by a red rectangle) offers a more user-friendly representation of values, with the precise time of each reading when a point on the graph is selected.

Finally, two horizontal red lines are present in the temperature and soil moisture graphs. In the first graph, the red line symbolizes the minimum temperature (2 °C), below which the irrigation of apple trees is not recommended. The second red line in the second graph represents the maximum moisture threshold (70%), above which excess water is avoided for good soil condition.

The same elements from the dashboard of the first sensor are present in the dashboard of the second sensor, GALA, except for the values, which change due to the difference in location.

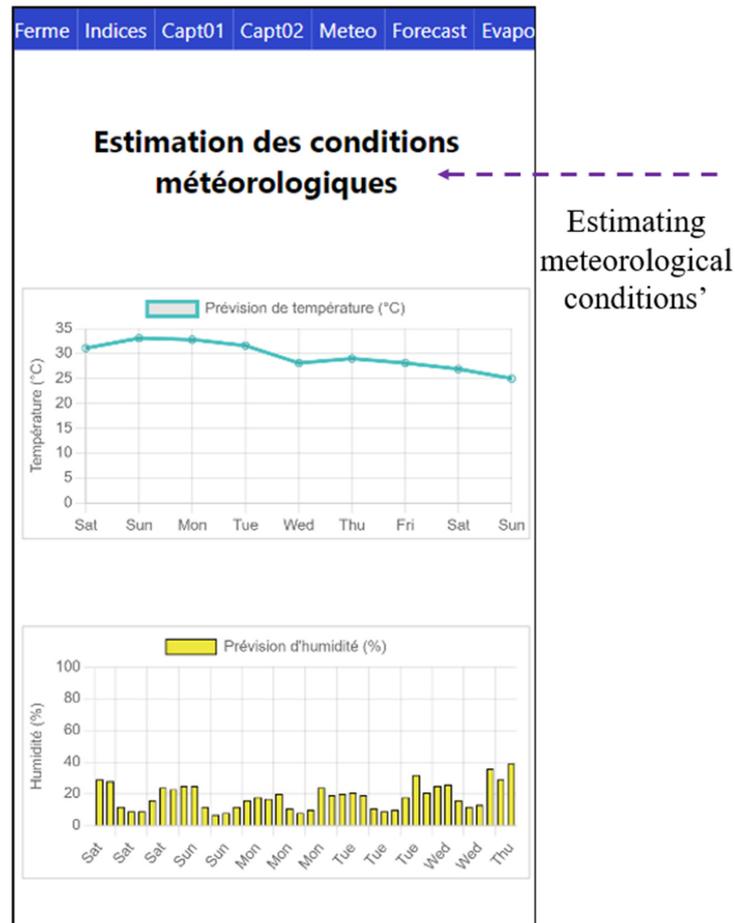


Figure A6. Page 1 of weather estimation service.



Figure A7. Page 2 of weather estimation service.



Figure A8. Page 3 of weather estimation service.

In this service, we provide users with short-term weather forecasts. The following is worth knowing:

- Air temperature;
- Air humidity;
- Wind speed;
- Ground pressure;
- Accumulated precipitation;
- Outgoing solar radiation (LongWave);
- Incoming solar radiation (ShortWave);

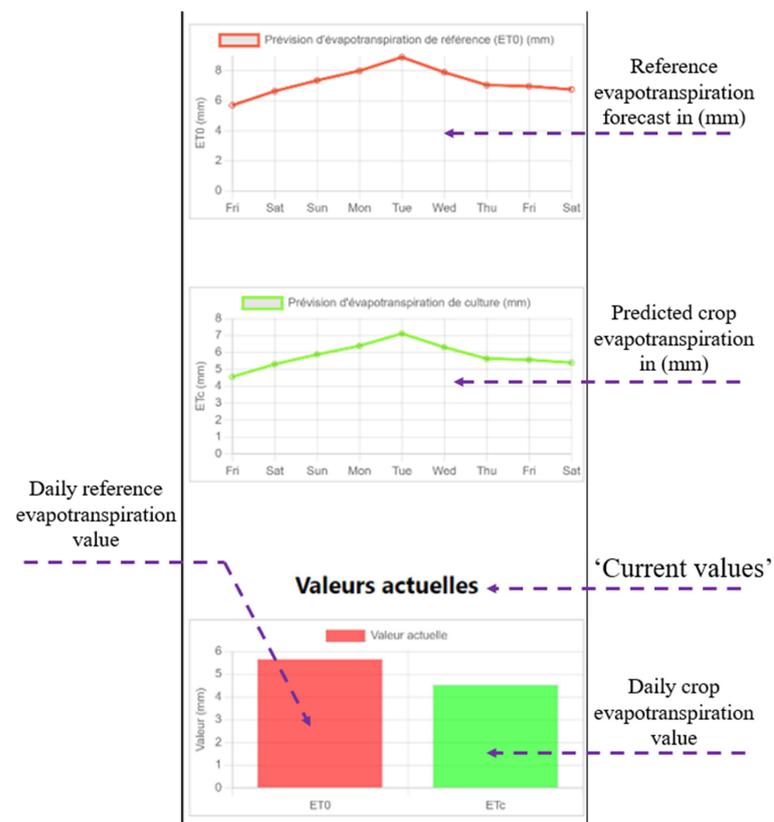


Figure A9. Evapotranspiration estimation.

This service presents future values of reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c) for the next 8 days. It also provides the corresponding values for the current day (daily). The graphs at the top allow the user to easily observe and understand the ET_o and ET_c forecasts. By clicking on a point on the graph, a small pop-up window displays the values and the time of the forecast. At the bottom of the page, the current day's values for these two parameters are displayed.

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