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WP5
D5.3 Report on the design and test application of quasi-operational digital spatially explicit information services

Spatially Explicit Digital Twin of the Greek Agro-Hydro-System

ID 14815

Greece 2.0 NATIONAL RECOVERY AND RESILIENCE PLAN
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1. Introduction

The primary objective of Work Package 5 (WP5) is to translate the advanced modelling capabilities of the DT-Agro Digital Twin into functional, quasi-operational information services. These services are designed to provide regular, spatially explicit updates on the state of the agro-hydro-system to support decision-makers, researchers, and agricultural stakeholders.

While Deliverable D2.1 established the algorithmic core (hydrology, crop growth, erosion) and Deliverable D2.2 defined the system architecture and integration framework, this report (D5.3) demonstrates how these components combine to form an operational service pipeline.

The DT-Agro system goes beyond static modelling by creating a dynamic "Digital Twin" that ingests continuous Earth Observation (EO) data streams, such as Sentinel-2 imagery and AgERA5 reanalysis, to update internal state variables (e.g., soil moisture, crop phenology). This report documents the design of these services, the automated workflows that sustain them, and the results of a comprehensive national-scale test application (1971–2024), the full details of which are available in D4.2.

2. System Architecture and Data Flow

The DT-Agro architecture is a modular, layered system designed for scalability and interoperability. It couples a high-performance **C++ simulation engine** with flexible **Python-based data workflows** to handle the vast heterogeneity of spatial data required for national-scale modelling.

2.1 Architectural Layers

For a complete technical specification of the system components, readers are referred to D2.2 (System Architecture). The system is organized into three primary layers:

1. **Data Acquisition & Pre-processing Layer:** This layer consists of Python modules that automate the retrieval and harmonization of external datasets. Key components include the EO pipeline for Copernicus Land Monitoring Service (CLMS) products and the meteorological processing chain for AgERA5 and station data.

2. **Modelling Core Layer:** The computational heart of the system is the **AgroHydroLogos** model, fully recoded in C++ for efficiency. It operates on a dual-resolution grid (1 km for meteorology, 100 m for agro-hydrology) and handles water balance, crop water use, and erosion processes.
3. **Orchestration & Interface Layer:** Implemented in Python, this layer manages job scheduling, parallel execution via domain decomposition, and the export of results to user-facing formats (GeoTIFF, NetCDF).

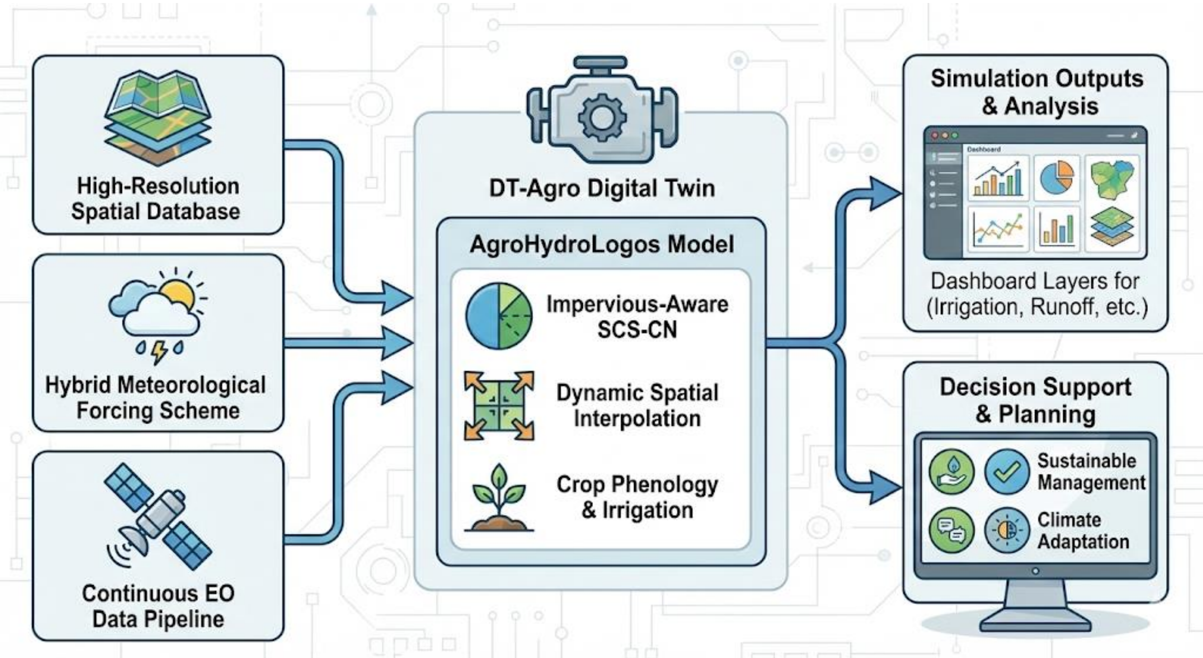

Figure 1. DT-Agro architecture.

2.2 The "Virtual Station" Data Pipeline

A critical innovation detailed in D2.1 is the "Virtual Station" framework, designed to overcome the limitations of raw reanalysis data in complex terrain. The pipeline operates as follows:

- **Sampling:** AgERA5 reanalysis data is sampled daily at the locations of ~140 historical meteorological stations.
- **Bias Correction:** Station-specific regression models correct the reanalysis data against historical observations, creating "virtual stations" that are temporally complete but locally accurate.
- **Dynamic Interpolation:** These corrected records serve as input for a dynamic spatial interpolation scheme that accounts for temperature and precipitation lapse rates, generating forcing grids for the entire country.

3. Digital Information Services

DT-Agro currently supports three primary quasi-operational services. These services utilize the algorithms documented in D2.1 to transform raw data into actionable spatial indicators.

Service 1: National Irrigation Water Requirement Monitoring

- **Purpose:** To quantify net irrigation water requirements (NIR) and total abstractions at multiple scales, supporting water resource planning and policy compliance (e.g., WFD reporting).
- **Methodology:** The service combines daily soil water balance modelling with dynamic crop phenology derived from Sentinel-2 NDVI. It calculates the difference between potential evapotranspiration (ETc) and effective precipitation/soil moisture storage.
- **Output Indicators:**
  - **Net Irrigation Requirement (mm):** Spatially distributed demand per crop.
  - **Total Abstraction (hm³):** Aggregated volumes per river basin or administrative unit, accounting for distribution efficiencies.
  - **Crop Water Deficit:** Indices of water stress when demand is not met.
- **User Utility:** Enables the identification of high-demand zones and the assessment of drought impacts on specific crops.

Service 2: Agro-Hydrological State Monitoring

- **Purpose:** To provide a daily "health check" of the agricultural environment, monitoring soil moisture status and runoff potential.
- **Methodology:**
  - **Impervious-Aware Runoff:** Uses a novel Two-CN formulation (see D2.1) that splits each 100-m cell into pervious and impervious fractions based on Copernicus data, improving runoff accuracy in mixed landscapes.
  - **Soil Moisture Tracking:** Simulates daily root-zone water content based on hydraulic properties from the harmonized soil database.
- **Output Indicators:**
  - **Root-Zone Soil Moisture (%):** Daily maps indicating drought or saturation risk.
  - **Surface Runoff & Recharge (mm):** Daily fluxes for flood risk and aquifer replenishment analysis.

Service 3: Soil Erosion Risk Assessment

- **Purpose:** To assess potential soil loss and sediment transport, aiding in the design of conservation measures.
- **Methodology:** Integrates a dynamic RUSLE-based module. Unlike static assessments, this service updates the Cover Management factor (C) seasonally using EO vegetation indices and calculates rainfall erosivity (R) from daily precipitation events.

- **Output Indicators:**
    - **Gross Soil Loss (t/ha/y):** Potential erosion rates at 100-m resolution.
    - **Sediment Delivery:** Estimation of sediment loads reaching stream networks.

4. Implementation Tools and Automation

To ensure these services can run quasi-operationally, specific software tools were developed (detailed in D2.2):

- **EO Data Engine:** Automated Python scripts that query APIs (CDS, ESA) to download, reproject, and resample new satellite products to the EGSA87 reference system.
- **Serialization Algorithm:** A specialized C++ routine that converts grid data into binary streams, optimizing I/O operations and enabling the rapid processing of massive national datasets.
- **GUI Configuration:** A user-friendly Python interface that allows operators to define simulation periods, select inputs, and configure interpolation settings without modifying source code.

5. Demonstration and Testing (Test Application)

The system's operational readiness was validated through a comprehensive historical application covering the period 1971–2024. Full validation metrics and extensive analysis are provided in D4.2; key findings are summarized below.

5.1 Irrigation Abstraction Results

The test application demonstrated that DT-Agro can realistically reproduce national irrigation dynamics:

- **National Volumes:** Simulated total irrigation abstractions fluctuated between **6,000 and 7,800 hm³/year**, with a long-term average of **~6,600 hm³**.
- **Inter-annual Variability:** The system successfully captured the high variability driven by climate conditions, revealing a high-demand tail in the probability distribution that is critical for drought planning.
- **Crop Specifics:** Net irrigation depths were consistent with agronomic benchmarks:
    - **Maize/Cotton/Alfalfa:** 380–420 mm/year.
    - **Olive/Vineyards:** Consider deficit irrigation patterns to present more realistic results.

5.2 Hydrological and Meteorological Validation

- **Meteorology:** The "Virtual Station" approach significantly reduced biases in precipitation and temperature compared to raw AgERA5 data, particularly in mountainous regions.
- **Hydrology:** Validation against historical streamflow records yielded Nash-Sutcliffe Efficiency (NSE) values generally above 0.5 and PBIAS within ±25% for major gauged basins, confirming the model's reliability for regional water balance assessments.

6. Challenges and Future Outlook

While the system is quasi-operational, several challenges identified in D2.2 guide future development:

- **Soil Data Uncertainty:** Global datasets (SoilGrids/ESDAC) showed low accuracy when compared to Greek national data. Future iterations will integrate the new national soil data hub to improve parameterization.
- **IoT Integration:** Currently, the system relies primarily on EO data. Future phases will integrate real-time IoT sensor data (soil moisture, flow meters) for continuous calibration and state updating.

7. Conclusions

The work presented in this report, built upon the foundations of D2.1 and D2.2, confirms that DT-Agro has successfully moved towards transitioning from a model to a Digital Twin.

The system demonstrates the capability to:

1. **Ingest and Harmonize** diverse data streams (EO, Reanalysis, Static GIS).
2. **Process** these inputs through physically based, valid algorithms (AgroHydroLogos).
3. **Serve** critical information on irrigation, hydrology, and erosion at a national scale.

The initial application results (D4.2) validate the system's biophysical realism, with abstraction estimates (~6,600 hm^3/year) and spatial patterns aligning well with expert knowledge and available statistics. DT-Agro is thus ready for quasi-operational deployment to support sustainable agricultural and water management in Greece.

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