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WP1
D1.3 Project Impact evaluation report

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

DT-Agro

ID 14815

Greece 2.0 NATIONAL RECOVERY AND RESILIENCE PLAN
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Plan Details

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1. **Introduction**

This deliverable presents the final impact evaluation of the DT-Agro project at the conclusion of its 24-month implementation period. Its purpose is to assess the extent to which the project has achieved its scientific and technical objectives, as well as to evaluate the effectiveness of the project's management framework and risk-mitigation measures.

The report examines progress across all work packages and provides an integrated assessment of the results, methodologies and outcomes generated during the project. The evaluation reflects evidence gathered through internal monitoring, progress reports, deliverable outputs, dissemination activities and interactions with stakeholders, including research partners, agricultural organisations and field collaborators. The findings presented here offer a comprehensive overview of DT-Agro's impact and demonstrate the project's contributions to advancing digital-twin technologies, enhancing agro-hydrological understanding and supporting sustainable agricultural water management in Greece.

2. **Impact Evaluation**

2.1 Impact Assessment Methodology

The impact evaluation of DT-Agro was carried out using a **mixed qualitative–quantitative approach**, aligned with the project's Description of Action and with the monitoring requirements of the HFRI "Basic Research Financing" scheme.

The assessment combines:

- Evidence from **project documentation**, including all technical deliverables (e.g. D2.1, D2.2, WP3–WP5 reports), internal progress reports and meetings.
- **Scientific outputs**, such as peer-reviewed articles, conference papers and abstracts, and invited presentations directly linked to DT-Agro.
- **Data and infrastructure developments**, including the DT-Agro Digital Twin implementation, EO and soil-data workflows and the emerging national soil data hub.
- **Dissemination and stakeholder activities**, including presentations at national and international congresses, the Agrotica exhibition, workshops, policy briefs and direct interactions with farmers, regional authorities and professional organisations.

The evaluation is structured along four main dimensions:

1. **Scientific impact** – contributions to knowledge on agro-hydrology, climate and soil data evaluation, runoff and erosion modelling and digital-twin concepts.
2. **Technical impact** – development of new methods, tools and software components, including the DT-Agro architecture, algorithms and operational workflows.
3. **Data and infrastructure impact** – creation and enhancement of datasets, data hubs and processing chains that will remain available beyond the project's lifetime.
4. **Dissemination, communication and stakeholder impact** – communication of results, engagement with end users and authorities and support for policy development and capacity building.

For each dimension, the evaluation considers:

- the **degree of objective fulfilment**,
- the **quality and robustness** of the results (e.g. through validation, peer review), and
- the **sustainability and potential for future use** of the outputs (e.g. DT-Agro as a long-term Digital Twin infrastructure, soil data hub, methods transferable to other projects).

2.2 Scientific Impact

DT-Agro has generated **substantial scientific outputs** that directly address key limitations in agro-hydrological modelling and data availability in Greece:

- **Evaluation of global climate datasets for small-scale agriculture.** A peer-reviewed article in *Atmosphere* assessed the performance of AgERA5 and MERRA-2 for irrigation management in the Nemea viticultural region, quantifying biases and uncertainties in daily precipitation and reference evapotranspiration and demonstrating the need for local bias correction before use in precision irrigation.
- **Advances in gap-filling solar radiation and meteorological time series.** A paper in *AIMS Geosciences* systematically compared empirical and machine-learning approaches for reconstructing missing solar-radiation data from routine meteorological variables, providing guidance on method selection and highlighting the conditions under which machine learning (ML) methods offer added value.
- **Critical evaluation of global/pan-European soil datasets.** A study in *Soil Systems* compared ISRIC and ESDAC digital soil maps with the Greek Soil Map using more than 10,000 samples, revealing low accuracy for texture classes, high RMSE values for texture fractions and weak explanatory power, while also identifying geomorphological and lithological patterns in the errors.

In addition, DT-Agro has supported **ongoing and emerging scientific work**, including:

- a manuscript currently under review in *Hydrological Sciences Journal* proposing a **simplified method to account for watershed heterogeneity in SCS-CN runoff**

estimation, closely linked to the improved runoff formulation implemented in DT-Agro;

- a paper in preparation presenting the **development and first application of DT-Agro** as a national-scale Digital Twin of the Greek Agro-Hydro-System;
- comparative analyses of **PESERA vs (R)USLE** concepts in the Nemea region, supporting the erosion-modelling strategy adopted in the project.

DT-Agro results have also been disseminated through **major scientific events** (e.g. EGU, IAHS), with contributions on SCS-CN parameter estimation, climate-dataset evaluation, digital soil maps in comparison with laboratory data and EO-based soil moisture. These activities provide the theoretical and empirical foundations for the Digital Twin and increase its international visibility.

Overall, the project has **clarified the limitations** of widely used global climate and soil products, **introduced new methods** (virtual stations, improved SCS-CN formulation, soil-data evaluation) and **positioned DT-Agro** as a scientifically grounded example of a national-scale agro-hydrological Digital Twin.

2.3 Technical Impact

On the technical side, DT-Agro has delivered a functioning Digital Twin engine that integrates modelling, Earth Observations (EO) and data workflows:

- The **AgroHydroLogos core** was recoded and optimised in C++, with dual spatial resolution (100 m - 1 km meteorology, 100 m agro-hydrological processes), domain decomposition, parallelisation and an improved runoff-routing component.
- A new Python-based orchestration and EO integration layer was developed to retrieve, preprocess, bias-correct and interpolate meteorological data; process Sentinel- and Copernicus-based EO products; and prepare harmonised input rasters and time series for the C++ core.
- The project implemented novel algorithms for:
  - spatially and temporally distributed rainfall and temperature gradients across Greece,
  - hybrid meteorological forcing using virtual stations (AgERA5 + station bias correction), and
  - an impervious-aware SCS-CN runoff computation at grid-cell level.
- The original ArcGIS-based interface was replaced with a platform-independent, open-source Python/GIS interface, allowing DT-Agro to run on different operating systems and computing infrastructures without dependence on proprietary desktop software.

These developments have transformed the original AgroHydroLogos model into a modular Digital Twin platform that can:

- run multi-decadal simulations at national scale,

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- integrate new EO products and data streams as they become available, and
- support future extensions (nutrient loads, pollution, soil-health indicators) without re-engineering the entire system.

2.4 Data and Infrastructure Impact

A central outcome of DT-Agro is the creation and consolidation of data assets and infrastructure that will outlive the project:

- A harmonised national geospatial database for DT-Agro, including DEM derivatives, meteorology, soils, land cover/crops, imperviousness and model parameter maps at 100 m and 1 km resolution, organised in a documented directory structure and using standard formats (GeoTIFF, NetCDF, CSV/Parquet).
- A hybrid meteorological forcing dataset based on virtual stations: complete, bias-corrected daily time series for ~140 locations, interpolated to a 1 km grid for the full AgERA5 period, providing a long-term, internally consistent climate basis for modelling and climate-change studies.
- The initiation of a national soil data hub, currently integrating more than 17,000 georeferenced soil sampling points from multiple campaigns and sources, used to evaluate and improve digital soil maps for Greece and to derive improved soil-property layers tailored to Greek conditions.
- EO-based processing chains for Sentinel-2 crop mapping and Sentinel-1/2 soil-moisture estimation, which are directly linked to DT-Agro through land-cover, crop-type and surface soil-moisture layers at high spatial resolution.

These assets are exposed through the Open Access Research Portal and Database (D6.3), which hosts EO data (e.g. NDVI, imperviousness), harmonised land-cover layers, meteorological datasets and evaluation statistics, soil datasets, hydrological terrain derivatives, Digital Twin outputs (e.g. CN maps, soil-moisture and ET simulations, preliminary scenarios) and field data (soil moisture, irrigation measurements). The portal is organised into thematic categories and is designed to remain active and expandable beyond the project's end, supporting long-term reuse and collaboration.

Together, these data assets constitute a durable infrastructure for agro-hydrological analysis in Greece, reducing dependence on uncertain global datasets and enabling more precise and transparent assessments of water, soil and crop dynamics.

2.5 Dissemination and Communication Impact

Beyond the considerable number of scientific publications listed in D6.5, DT-Agro has achieved broad dissemination and communication activities across scientific, professional and stakeholder communities. It should be noted that, given that the project duration was only two years, many aspects of the project and its results will be published in the following years.

A central element is the project website hosted by the GIS Research Unit of the Agricultural University of Athens, which presents the project's objectives, methodology, work-package structure, deliverables, publications and news. This digital presence ensures that project information, results and updates are accessible to a wide audience beyond the immediate consortium and will remain a long-term reference for DT-Agro after the end of the funding period.

DT-Agro has also been actively disseminated through specialised social media channels and the social media channels of the GIS Research Unit:

- the **Instagram account**, which communicates news and visual material on geospatial technologies in digital agriculture and the environment, including posts related to DT-Agro activities, events and publications;
- the **DT-Agro Facebook presence**, which highlights key milestones (e.g. published articles, conference contributions) and directs followers to the project website and portal.

In addition to online channels, DT-Agro's concept, methodology and first results have been presented at:

- major international conferences (EGU, IAHS) and
- national conferences and workshops (e.g. GIS & Spatial Analysis in Agriculture and Environment conference)

The presentation of DT-Agro and its applications is also planned to take place at the Agrotica exhibition, strengthening links with practitioners, regional stakeholders and industry. Further, a special session is being organised in the 6th Congress of Geographical Information Systems and Spatial Analysis in Agriculture and Environment, 19 - 21 May 2026, Conference Center of the Agricultural University of Athens, where the operational DT-Agro Digital Twin, its applications and future perspectives will be presented.

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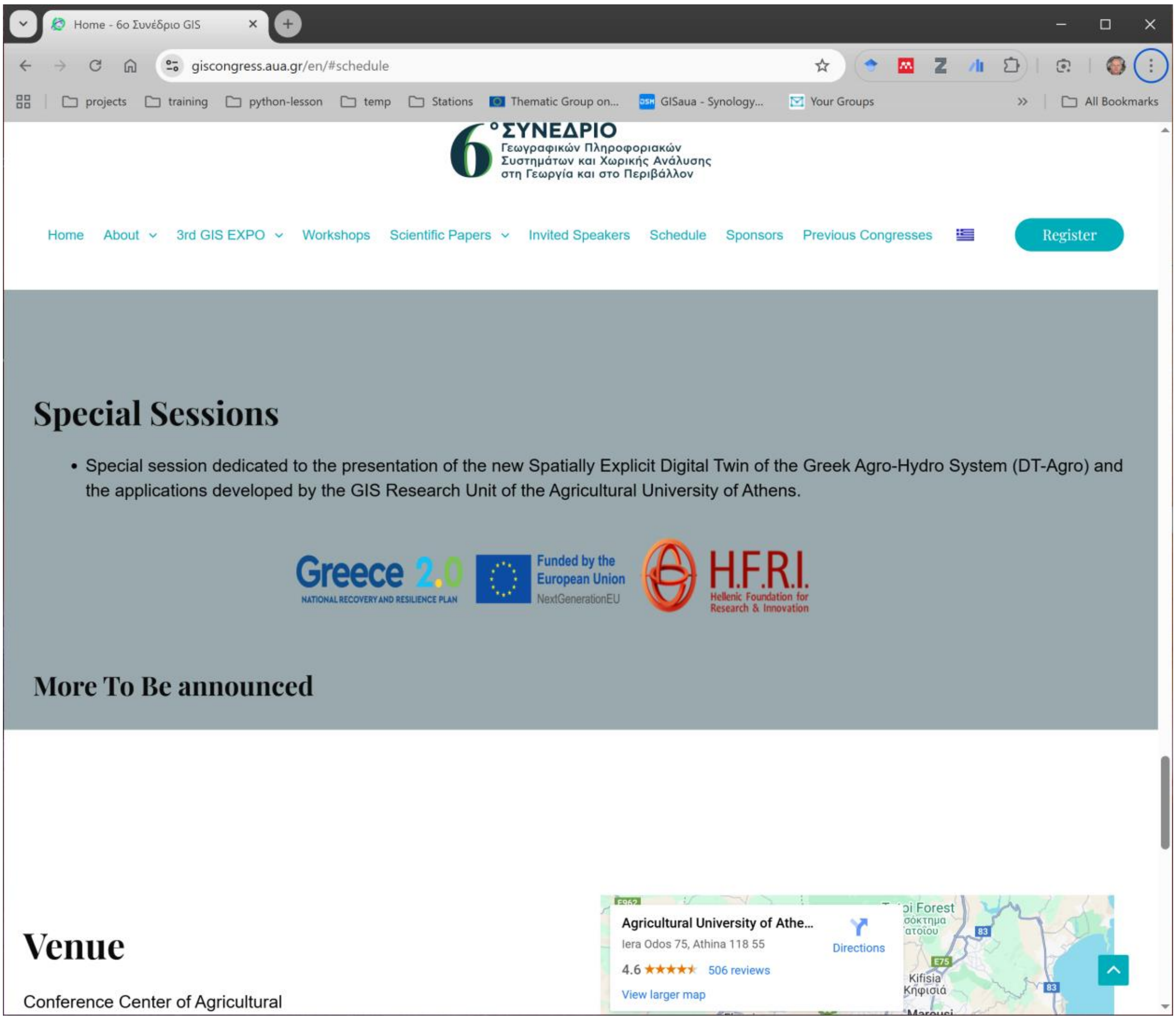

Figure 1. Print screen of the website of the congress with the announcement of the special session.

Presentations were also made at meetings with farmers and cooperatives, for instance at the meeting organised at the cooperative of Nea Karya Kavala (27 May 2025) during one of the field trips to collect data on cultivations, water consumption and soil properties.

Figure 2. Meeting with farmers and representatives of the Nea Karya Kavala cooperative (27 May 2025) during DT-Agro field activities, including presentations and discussions on project objectives.

Finally, a policy brief was created based on the initial results that will be disseminated through the project's channels.

The **Dissemination, Communication and Exploitation Plan (DCEP)**, updated in D6.1b, has guided these activities with clear target groups (researchers, policymakers, farmers, industry, and the general public) and coordinated messaging.

2.6 Stakeholder Impact

DT-Agro's impact on stakeholders is still emerging but already **tangible** in several areas:

- **Farmers and agricultural advisors** have been exposed to DT-Agro concepts and preliminary results through Agrotica, congress workshops and direct discussions. This has illustrated how spatially explicit information on irrigation needs, soil moisture and soil conditions can support more efficient water use and climate-smart practices.
- **Public authorities and policy bodies** (e.g. ministries, regional water authorities) have been engaged through the linkage of DT-Agro outputs to CAP and RDP impact indicators (e.g. water-abstraction indicators, nitrate-reduction actions), building on earlier evaluation work and indicator analyses.
- The project has contributed to capacity building, involving PhD candidates, postgraduate students and young researchers in all stages of the work, from model development and EO processing to data-hub construction and dissemination. Two PhD theses and several MSc-level works have been supported directly or indirectly by DT-Agro, helping to grow national expertise in Digital Twins, agro-hydrology and geospatial analysis. It is important to note that the largest share of the project budget was dedicated to supporting two PhD students working on the project.

Importantly, DT-Agro has opened new channels of dialogue between researchers, practitioners and policymakers, positioning the Digital Twin as a potential scientific reference tool for future discussions on drought, irrigation and soil-management strategies in Greece.

2.7 Review of Data Management and Risk Mitigation Measures

The project adopted a structured data management approach, consistent with open-science principles and tailored to the specificities of large geospatial and EO datasets:

- Data are stored in a well-documented file-based geodatabase, with clear separation between raw, intermediate and model-ready products and the use of open formats (GeoTIFF, NetCDF, CSV/Parquet).
- Standardised naming conventions, versioning and directory structures ensure traceability from raw EO and station data to the rasters and time series actually used in simulations.
- Backups and redundancy are ensured at the level of raw EO data, critical soil and meteorological datasets, and key model outputs, reducing the risk of data loss.

From a risk-mitigation perspective, DT-Agro had to address three main categories of risk:

1. **Data quality and availability risks** – uncertainties and gaps in reanalysis meteorology, global soil datasets and EO products.
    - *Mitigation:* systematic evaluation of these datasets, development of the virtual-station concept, establishment of the national soil data hub and use of multiple sources (e.g. IACS + Sentinel-2 for crops).
2. **Technical and operational risks** – potential delays or failures in integrating EO workflows and recoded model components.
    - *Mitigation:* modular architecture; decoupling of C++ core and Python orchestration; progressive integration with clear intermediate milestones (D2.1, D2.2).
3. **Stakeholder and uptake risks** – uncertainty about end-user acceptance and use of DT-Agro outputs.
    - *Mitigation:* early and repeated engagement through exhibitions, workshops, policy briefs and direct discussions with farmers and authorities.

Overall, the risk-mitigation measures proved effective: the core scientific and technical objectives were achieved within the planned period, and the groundwork was laid for continued development and uptake beyond the project's formal end.

2.8 Alignment with Original Objectives and Greece 2.0 Priorities

The DT-Agro project was conceived with six main objectives: to (i) develop a spatially distributed Digital Twin of the Greek agro-hydrosystem, (ii) evaluate and integrate efficient algorithms for hydrology, crop water use and soil erosion, (iii) identify and streamline EO and ancillary data as inputs and evaluation datasets, (iv) apply the Digital Twin in a national-scale pilot study, (v) analyse the large volumes of spatial data generated and (vi) disseminate results through open-access databases, publications and targeted communication activities.

The impact evaluation confirms that these objectives have been **substantially achieved** within the 24-month project period, with remaining refinements embedded in the associated work plan:

- A functional Digital Twin prototype producing spatially distributed simulations of water-balance components, crop water stress, irrigation needs and soil erosion for the Greek territory.
- Core algorithms for hydrology, crop growth and erosion were evaluated, adapted and implemented with improved computational efficiency, fulfilling the modelling milestones and enabling national-scale simulations.
- Automated workflows were established for AgERA5 and other meteorological products, Copernicus land-cover and imperviousness datasets, and EU-DEM, resulting in a harmonised 100 m geospatial database and a bias-corrected meteorological forcing framework based on the virtual-station concept.

- National-scale pilot simulations (WP4) and subsequent analyses (WP5) have demonstrated the ability of DT-Agro to estimate irrigation water requirements, water abstractions and related indicators at parcel, basin and national scales.

From a policy perspective, DT-Agro is closely aligned with the Greece 2.0 National Recovery and Resilience Plan priorities on digital transformation, sustainable agriculture and climate resilience.

The project delivers a digital infrastructure that supports evidence-based management of water and soil resources, contributes to climate-smart agricultural planning and provides tools that can inform CAP-related measures and eco-schemes. The policy brief on "Drought and Irrigation Challenges in Greece" further translates DT-Agro concepts into concrete recommendations for water governance, irrigation efficiency and climate adaptation, illustrating the project's relevance for national policy debates.

3. Conclusions and Outlook

The DT-Agro project has successfully demonstrated the feasibility and added value of a national-scale Digital Twin for the Greek agro-hydrosystem. It has delivered a coherent framework that integrates EO data, ground observations and numerical modelling to simulate key agro-environmental processes at 100 m resolution, including runoff generation, infiltration, evapotranspiration, crop water stress, irrigation demand and soil erosion.

On the scientific and technical side, the project advances the state of the art in spatially distributed agro-hydrological modelling by:

- extending the AgroHydroLogos framework into a modular Digital Twin architecture with improved computational efficiency;
- implementing bias-corrected meteorological forcing based on virtual stations that combine sparse observations with reanalysis products;
- harmonising multi-source land-cover, soil and topographic datasets into a national geodatabase; and
- operationalising EO-driven workflows for NDVI, imperviousness, soil properties and other key variables.

The data and infrastructure impact is reflected in the open-access research portal and database, which provides selected DT-Agro datasets, documentation and scripts for reuse by researchers and practitioners. The automated EO pipelines and modular codebase form a reusable backbone for future Digital Twin initiatives in agriculture and water management.

In terms of communication, stakeholder and policy impact, DT-Agro outputs have been disseminated through peer-reviewed articles, international conferences (EGU, IAHS), the project website, social media channels and a dedicated policy brief addressing drought and irrigation challenges in Greece. These activities have increased the visibility of Digital Twin concepts among scientists, water authorities and agricultural stakeholders and laid the groundwork for future co-design of operational services.

At the same time, the evaluation recognises remaining limitations and open challenges, notably:

- data scarcity and uncertainty for long-term meteorological and soil observations,
- the complexity of national-scale model calibration, and
- the need for further development of quasi-operational information services and stronger IoT integration.

These issues have been transparently documented in the risk and implementation reports, and mitigation strategies, including bias-correction methods, expanded soil sampling, the soil data hub and prioritisation of core indicators, are already in place.

Looking ahead, the integration of DT-Agro within an ongoing PhD programme ensures continuity beyond the formal project end. Remaining tasks include the refinement of advanced analyses and scenarios, incorporation of additional EO products (e.g. soil moisture, LAI), further development and testing of digital, spatially explicit agronomic services and deepening engagement with policy and user communities.

Overall, given that DT-Agro involved a very ambitious and critical objective, the impact evaluation concludes that DT-Agro has delivered a coherent and robust set of scientific and technical outputs and created a solid foundation for future research and operational deployment. The project contributes directly to Greece 2.0 goals by strengthening digital capacities in agriculture, supporting climate-resilient water management and enabling more informed, data-driven policy and farm-level decisions.