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## WP5

**D5.2 Report on Greek Agro-Hydro-System functioning, water, soil  
and environmental issues and climate change impact and  
mitigation and adaptation strategies**

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



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## Plan Details

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### 1. Introduction

This deliverable (D5.2) interprets the functioning of the Greek Agro-Hydro-System using the DT-Agro Digital Twin and the analytical workflows developed in WP3–WP5.

The report is anchored on the final national-scale DT-Agro test application (D4.2) and the corresponding open spatial database of outputs (D4.3). The analyses combine process-based simulations with Earth Observation (EO) indicators (e.g., NDVI-derived crop coefficients, vegetation water deficit and satellite soil-moisture proxies) and hybrid meteorological forcing based on bias-corrected virtual stations.

The focus is on: (i) hydroclimatic gradients and water-balance partitioning (precipitation, reference evapotranspiration  $E_{To}$ , potential crop evapotranspiration  $E_{Tp}$ , actual evapotranspiration  $E_{Ta}$  and direct runoff), (ii) irrigation demand and drought-year risk at national and regional scales, (iii) soil and land-surface controls (soil water-holding capacity, land cover and imperviousness, curve number), and (iv) implications for water, soil and environmental issues, including climate change impact and mitigation/adaptation strategies.

Unless stated otherwise, results are interpreted over 1974–2024 (following the 1971–1973 warm-up) and can be explored through the DT-Agro research portal described in D4.3.

### 2. Data and Methodological Framework

This section summarizes the main datasets, processing tools, and analytical methods applied in the present analyses. Deliverable 3.2 documented the operational workflows for EO data acquisition and transformation, while Deliverable 5.1 established the analytical foundation for data harmonization and validation. The current work applies those procedures to produce the results presented in later sections, focusing on meteorological, soil, vegetation, and hydrological components.

DT-Agro was configured for a first country-scale application covering the entire territory of Greece (~132,000 km<sup>2</sup>). The modelling follows a dual-resolution design: meteorological

forcing fields are produced at 1 km, while agro-hydrological computations (soil water balance, crop evapotranspiration, irrigation needs and related outputs) are performed at 100 m. Simulations were conducted at a daily time step for 1971–2024, with 1971–1973 used as a warm-up period; therefore, most analyses focus on 1974–2024.

Land use and crop information for agricultural areas are derived from IACS (Integrated Administration and Control System) parcel declarations. For this initial pilot, a fixed national crop pattern (reference year 2018) was adopted to isolate meteorological variability from land-use change. Non-agricultural land cover and imperviousness layers are obtained from Copernicus/CORINE products and are used to parameterise runoff generation and surface processes.

Meteorological forcing is derived from AgERA5 reanalysis variables combined with station observations through a hybrid “virtual station” approach. For each of ~140 stations, AgERA5 time series were bias-corrected using station-specific regressions (when observations were available) to create continuous corrected records over 1971–2024. During model execution, the corrected virtual-station fields are dynamically interpolated to the 1 km forcing grid using distance-based methods with elevation-dependent adjustments for precipitation and temperature. This approach preserves the spatio-temporal completeness of reanalysis while anchoring the forcing to the observed local climatology.

Soil data are derived primarily from the Greek Soil Map compiled by OPEKEPE, complemented by international datasets from ISRIC and ESDAC where national coverage is incomplete. These datasets were compared and evaluated as described in D5.1 in order to determine consistency and suitability for DT-Agro applications. The combined soil information supports the calculation of hydrological properties and is used for further integration in the Digital Twin.

The Copernicus Digital Elevation Model at 30-metre resolution provides the topographic basis for DT-Agro. The DEM was processed, reprojected and harmonized according to the methods described previously, supporting hydrological calculations and the representation of spatial terrain characteristics. In addition, land use and land cover information is obtained from the CORINE Land Cover dataset and the CLC Backbone of the Copernicus Land Monitoring Service (CLMS). These products provide detailed land cover classifications for Greece and enable the identification of cropland, forest, grassland and urban areas, which are required for the spatial analyses presented in this deliverable.

Vegetation indices, particularly the Normalized Difference Vegetation Index (NDVI), are a core component of the EO input. The NDVI dataset used in DT-Agro originates from the Copernicus Global NDVI 300-metre Version 2 product, derived from Sentinel-3 OLCI observations and distributed through the Copernicus Global Land Service. Data are provided as 10-day composites in NetCDF format with integer-scaled values. Following the procedure established in D3.2, NDVI values were converted to physical units using the scaling relation  $NDVI_{real} = (DN \times 0.004) - 0.08$ . Invalid and sea pixels were removed based on quality flags,

and the resulting rasters were reprojected to the national coordinate system EGSA87 (EPSG:2100) and resampled to a 100-metre grid to ensure spatial compatibility with other datasets. These harmonized products were then used to estimate crop coefficients ( $K_c$ ) through the empirical formulation of Montgomery et al. (2015) and to compute actual evapotranspiration ( $ET_c$ ) in combination with reference evapotranspiration ( $ET_o$ ) derived from AgERA5.

The DT-Agro data pipeline established in D3.2 was implemented using Python programming and open-source geospatial libraries such as xarray, rasterio, and pandas. Automated scripts were developed to interact with the Copernicus APIs, download EO products, convert file formats, and prepare datasets for ingestion into the DT-Agro spatial database. The same environment was used for the aggregation of AgERA5 daily data into monthly means or totals, facilitating consistency between EO and reanalysis variables.

Between July 2024 and July 2025, several field campaigns were conducted across Greece to collect ground-truth datasets regarding soil moisture, crop water stress, and irrigation consumption, which are being used to evaluate the accuracy of the model. In July 2024, irrigation water consumption measurements were carried out in Katerini and Kavala. In May 2025, soil-moisture and water-stress data were collected using unmanned aerial vehicles in cooperation with local farmers in Kavala and Xrysoupoli. In June 2025, additional soil and irrigation loss measurements were made in Peloponnese. Further measurements, including leaf-area index and chlorophyll content, were taken between in July 2025 in Karditsa, Skydra, and Lamia. Data from over 40 operational soil-moisture and irrigation withdrawals stations supplemented these campaigns. Together, these datasets provided an extensive basis for validating EO-based indicators and model simulations.

The analytical framework of DT-Agro combines remote sensing and process-based modeling through harmonized workflows. NDVI values are transformed into daily  $K_c$  time series, from which  $ET_c$  is computed by multiplying  $K_c$  with reference evapotranspiration. Surface runoff and infiltration processes are simulated using the Curve Number methodology adapted from Soulis and Valiantzas (2012), which incorporates land-use, soil hydrological group, and imperviousness density data. Statistical evaluation of datasets is performed using bias, mean absolute error, root mean square error, and correlation coefficient indicators. All datasets are harmonized within the Greek national grid system and resampled to a 100-metre spatial resolution to allow seamless integration into the AgroHydroLogos model and the broader DT-Agro Digital Twin environment.

The following sections present the analysis and interpretation of the results obtained from these workflows, including the evaluation of meteorological and soil data, estimation of vegetation and crop water demand, simulation of hydrological responses, and integrated assessment of the Greek agro-hydrological system under current and evolving climatic conditions.

### 3. Analysis and Results of the DT-Agro functioning

This section presents the results and interpretation of the analyses performed using the DT-Agro Digital Twin framework. The focus is on evaluating the performance and accuracy of the datasets and models integrated into the system, including meteorological, soil, and vegetation data, as well as hydrological components related to surface runoff and water balance. The results reflect the first full application of the DT-Agro framework across Greece, combining reanalysis data, Earth Observation (EO) products, and ground-based information.

#### 3.1 Meteorological Data Evaluation

Meteorological data form the foundation of the DT-Agro Digital Twin. The AgERA5 dataset, which provides daily climatic variables at a spatial resolution suitable for agricultural applications, was evaluated against ground-based measurements from the Hellenic National Meteorological Service (HNMS) for the year 2023. This comparison aimed to quantify the level of agreement and identify systematic differences between observed and reanalysis data.

The analysis included 777 stations with available monthly data for temperature and precipitation. For each station, corresponding AgERA5 values were extracted from the nearest grid cell, converted into comparable units, and aggregated to monthly values. The statistical indicators used were bias, mean absolute error (MAE), root mean square error (RMSE), and Pearson correlation coefficient ( $r$ ).

For air temperature, the correlation between AgERA5 and observed data was high, with an average  $r$  value of 0.78. The mean bias was +0.45 °C, indicating a slight overestimation of observed temperatures. The MAE and RMSE were 2.06 °C and 2.44 °C, respectively, values that are within acceptable limits for regional climate validation studies. Spatially, the best agreement was found in the lowland and coastal regions, while some discrepancies occurred in mountainous areas where microclimatic variations are more pronounced. These results confirm that AgERA5 provides an accurate representation of temperature variability across Greece and is suitable for agricultural and hydrological simulations.

For precipitation, the agreement was more moderate, with an average correlation of 0.29 and a mean bias of -2.75 mm, indicating a tendency toward underestimation. The MAE and RMSE were 34.94 mm and 52.01 mm, respectively. Regional differences were significant, especially in mountainous and coastal areas where localized rainfall events are difficult to capture at the AgERA5 grid resolution. Nevertheless, AgERA5 successfully reproduces the general spatial and temporal distribution of precipitation, making it an appropriate dataset for national-scale applications. These results justify its use as the main meteorological forcing dataset within the DT-Agro framework.

#### 3.2 Soil Data Accuracy Assessment

The performance of different soil datasets was evaluated to ensure that DT-Agro uses reliable inputs for hydrological and agro-environmental modeling. Three sources of data were compared: the Greek Soil Map (OPEKEPE), the global ISRIC SoilGrids dataset, and the European Soil Database (ESDAC). The evaluation focused on soil texture components (sand, silt, clay) and derived texture classes, which influence infiltration, runoff, and water-holding capacity.

For this purpose, raster values of sand, silt, and clay were extracted for all available sampling points in Greece and compared between the national and international datasets. The results revealed substantial discrepancies between global datasets and the Greek Soil Map. Correlation coefficients ( $R^2$ ) were generally low, ranging from 0.15 to 0.19 for sand, approximately 0.12 for clay, and less than 0.04 for silt. The RMSE for sand content reached up to 18.6%, significantly higher than the expected range for reliable soil texture predictions. These discrepancies are partly explained by the coarse resolution and generalization of the global datasets, which do not fully capture the geological and pedological complexity of Greece.

Spatial analysis showed that the largest differences occur in sandy coastal and island areas and in clay-rich plains of central Greece. These regions correspond to distinct parent materials that are not well represented in global predictive models. The overall agreement in soil texture classification was also low, indicating that the global datasets fail to reproduce local soil variability at the scale required for hydrological modeling. Consequently, the Greek Soil Map was selected as the primary dataset for DT-Agro, while ISRIC and ESDAC are used only as supplementary sources where national data are unavailable.

This assessment highlights the importance of high-resolution, ground-validated soil information in representing spatial heterogeneity. The results also provide a basis for future updates, as the DT-Agro infrastructure allows dynamic integration of improved soil data when they become available.

### 3.3 Vegetation and Crop Water Demand (NDVI-Kc-ETc)

Vegetation indicators derived from satellite data were used to estimate crop coefficients (Kc) and actual evapotranspiration (ETc) across Greece. The NDVI composites from the Copernicus Land Monitoring Service (CLMS) at 10-day intervals and 300-m resolution were processed to produce spatially continuous maps of vegetation activity. Using the empirical relationship proposed by Montgomery et al. (2015),  $K_c = 1.37 \times NDVI - 0.086$ , time series of Kc values were generated for major agricultural regions.

The results display clear seasonal patterns consistent with crop phenology. Kc values increased during the main growing period from April to July, reaching peak levels between 1.1 and 1.3 in irrigated areas with dense vegetation such as Thessaly and Central Macedonia. After harvest, values declined sharply, reflecting reduced canopy cover and lower

transpiration. In rainfed areas,  $K_c$  values remained lower and exhibited higher temporal variability due to water stress and intermittent rainfall.

Actual evapotranspiration ( $ET_c$ ) was estimated by multiplying  $K_c$  with reference evapotranspiration ( $ET_o$ ) derived from AgERA5 data using the FAO-56 Penman–Monteith equation. The resulting  $ET_c$  maps and time series captured the temporal evolution of crop water use. Monthly  $ET_c$  reached up to 150 mm in intensive cultivation zones during July and August, while in spring and autumn it remained below 30 mm, reflecting lower crop activity and temperature.

Validation against station data and modelled  $ET_c$  values confirmed good agreement between NDVI-derived  $ET_c$  and observed patterns, particularly in regions with homogeneous land cover and irrigated agricultural areas. Minor underestimations were observed in mixed or heterogeneous landscapes where NDVI saturation reduced sensitivity at high biomass levels and limited the representation of dense vegetation cover.

These results demonstrate the ability of EO-based indicators to represent dynamic crop water conditions and show the potential of DT-Agro to provide near real-time monitoring of evapotranspiration and crop stress at national scale. Such information is critical for water resources management, irrigation scheduling and climate-adaptation planning, and will be further developed as the system is extended to future climate scenarios and updated land-use conditions in the next stages of the project.

### 3.4 Runoff and Surface Hydrological Response

Surface runoff simulations were carried out using the Curve Number (CN) methodology implemented within DT-Agro. CN values were calculated by combining information from land cover, soil hydrological groups, and imperviousness density according to the simplified Two-CN method described by Soulis and Valiantzas (2012). In this approach, each grid cell is represented by a pervious and an impervious fraction, allowing dynamic adjustment of runoff potential depending on the degree of urbanization or soil sealing.

The national CN map indicates higher values in urban and densely cultivated plains, exceeding 85, while lower values, typically below 60, characterize forested and mountainous areas. The resulting spatial patterns of runoff potential correspond well with known hydrological behavior, confirming the consistency of the DT-Agro implementation.

Runoff simulations based on these CN layers reproduce the expected hydrological response under various rainfall conditions. Increased runoff coefficients are observed during heavy precipitation events, particularly in central and northern Greece, while in drier southern regions infiltration dominates. These results demonstrate that the model successfully represents the variability of surface hydrological processes and their dependence on soil, land cover, and climatic inputs.

### 3.5 Integrated Analysis of the DT-Agro

The national DT-Agro simulations provide a coherent picture of the dominant hydroclimatic gradients in Greece and how these translate into crop water demand, runoff generation and water-balance partitioning. Long-term mean maps (1974–2024) of ETo, precipitation, ETp, ETa and direct runoff reveal consistent spatial patterns and allow the identification of hotspots where water stress and environmental pressures are expected to be highest.

**Reference evapotranspiration (ETo):** ETo exhibits a clear north–south and west–east gradient and a strong elevation control. Higher values occur over lowland plains (e.g., Thessaly, Central Macedonia, eastern lowlands) and many Aegean islands where summers are warm and dry; lower values occur in mountainous regions (Pindos range, Epirus and Western Macedonia highlands) and parts of the western coastal zone where temperatures are lower and humidity is higher.

**Precipitation:** Mean annual precipitation shows the well-known west–east contrast of Greek climate. Highest totals occur along the Ionian coast and western slopes of Pindos due to orographic uplift, while precipitation decreases sharply across the interior plains and towards Attica and the Aegean islands. The frequent co-occurrence of high ETo and low precipitation in eastern and island regions drives high climatic dryness.

**Potential crop evapotranspiration (ETp):** ETp combines climatic forcing (ETo) with crop coefficients and therefore highlights areas of concentrated potential crop water demand. The highest ETp values occur in intensively cultivated irrigated plains (e.g., Thessaly and Central Macedonia) and selected coastal lowlands, where both ETo and irrigated crop cover are high. Lower ETp is simulated in rainfed systems and semi-natural vegetation due to lower crop coefficients and shorter effective growing seasons.

**Actual evapotranspiration (ETa) and water stress:** ETa reflects the degree to which potential demand is met given available root-zone water. In well-watered irrigated areas ETa approaches ETp, whereas in rainfed systems and dry regions ETa is often substantially lower than ETp due to soil-moisture limitation. The ETa–ETp contrast therefore provides an implicit spatial indicator of water stress and can be translated into explicit stress indices and yield-related indicators in subsequent DT-Agro developments.

**Direct runoff:** Direct runoff patterns result from the interaction of precipitation, soils, land cover and imperviousness through the impervious-aware Curve Number formulation. Runoff is generally higher in humid western and mountainous areas (higher precipitation, steep slopes and shallow soils) and in locations with high imperviousness. Lower runoff is simulated in semi-arid lowland agricultural regions with relatively permeable soils where infiltration and soil-water storage dominate. Overall, evapotranspiration dominates the water balance in most agricultural regions, while runoff becomes more relevant in the humid west and mountainous headwaters.

These spatial patterns provide a consistent basis for interpreting major water and environmental issues in Greece, including drought-driven irrigation pressure in dry eastern lowlands and islands, flash-runoff susceptibility in mountainous headwaters and urban/peri-urban areas, and the role of soils and land management in buffering climatic variability.

By linking outputs to IACS parcels, DT-Agro enables parcel-level and regional aggregation of irrigation requirements. At national scale (reference crop pattern), indicative irrigation abstraction totals over the irrigated area are:

- Wet year: 6033 hm<sup>3</sup> (≈492 mm)
- Average year: 6600 hm<sup>3</sup> (≈564 mm)
- Dry year: 7771 hm<sup>3</sup> (≈664 mm)

The difference between wet and dry extremes (~1700 hm<sup>3</sup>, corresponding to ~25–30% of the average) demonstrates the strong control of inter-annual climate variability on irrigation demand. Crop-specific mean annual net irrigation depths for key irrigated crops are consistent with reported practice (e.g., maize ≈386 mm, cotton ≈416 mm, fodder crops/alfalfa ≈414 mm), reflecting both crop phenology and their spatial distribution across dryness gradients.

Time-series analysis over 1974–2024 indicates pronounced year-to-year variability and only a weak long-term tendency (not statistically significant under the fixed crop-pattern assumption). Exceedance-probability analysis highlights that severe high-demand years can require roughly 20–30% more water than the long-term mean, supporting a risk-informed perspective for water-resources planning and drought preparedness.

Relationships between irrigation demand and controlling factors confirm expected behaviours: irrigation requirements generally increase with climatic dryness (ET<sub>o</sub>/precipitation) and decrease with higher root-zone soil water-holding capacity. The dispersion around these relationships underlines the importance of crop type, soils and management practices, motivating targeted adaptation strategies and continued calibration/validation where data are available.

#### 4. Validation

Validation follows a multi-layered approach appropriate for a national-scale Digital Twin: (i) inheritance of parameterisations previously tested with AgroHydroLogos in representative Greek basins and irrigated regions, (ii) plausibility checks against published water-balance estimates and reported irrigation practices, (iii) consistency checks using EO-derived indicators and the field campaigns conducted within the project, and (iv) sensitivity analyses focusing on dominant controls (soil water holding capacity, crop coefficients, curve numbers and impervious fractions).

Meteorological forcing quality was evaluated against HNMS observations and is further strengthened in the national simulations through the bias-corrected virtual-station scheme. Vegetation and evapotranspiration indicators were evaluated by comparing NDVI-based  $K_c/ET$  estimates with available station and model information, showing good agreement in homogeneous land-cover areas and expected limitations in heterogeneous landscapes (e.g., NDVI saturation).

Soil-moisture related information was evaluated using field measurements and data from operational soil-moisture stations. These datasets support the assessment of spatial and temporal patterns in DT-Agro outputs and provide an observational basis for continued refinement.

Irrigation-related processes were evaluated using field observations and collaboration with farmers (irrigation consumption measurements and plot-scale monitoring). Together with crop-specific plausibility checks at national scale, these observations support the consistency of simulated irrigation demand patterns.

## 5. Climate change impact and mitigation and adaptation strategies

DT-Agro supports the assessment of climate-related pressures on Greek agriculture by translating meteorological variability into spatially explicit indicators of dryness, crop water stress, irrigation requirements and runoff response. The national simulations (1974–2024) demonstrate that inter-annual climate variability is a dominant driver of irrigation demand, with dry years requiring substantially higher abstractions than wet years (~25–30% difference between extremes).

From an adaptation and planning perspective, exceedance-probability analysis indicates that infrastructure and management rules should be robust not only to average conditions but also to occasional high-demand years, where irrigation requirements can be ~20–30% higher than the long-term mean.

The following mitigation and adaptation strategy bundles can be evaluated and monitored within DT-Agro using indicators such as  $ET_a/ET_p$  stress, vegetation water deficit, net irrigation requirement, dryness index and runoff susceptibility:

- Demand management and irrigation modernisation: improve scheduling (weather/ $ET$ -based), reduce conveyance and application losses, and prioritise high-efficiency systems (e.g., drip) in hotspots of high dryness and recurrent deficits.
- Soil water retention and soil health: increase root-zone water-holding capacity through organic matter management, reduced tillage, cover crops and residue management; these measures reduce irrigation requirements and buffer drought impacts.
- Crop and management adaptation: adjust crop choices, cultivars and planting dates to avoid peak heat/drought periods; promote rotations and varieties with lower water demand or higher heat tolerance in dry regions.

- **Runoff and erosion control:** implement nature-based solutions (contour farming, buffer strips, terracing where appropriate) and reduce soil sealing; these reduce rapid runoff generation and improve infiltration and groundwater recharge.
- **Risk-informed drought preparedness:** use exceedance-probability metrics and spatial hotspot maps to design drought triggers, allocation rules and contingency plans for rare but severe high-demand years.

In parallel, DT-Agro can support mitigation co-benefits (reduced energy use for pumping through lower abstractions, soil carbon co-benefits from regenerative practices) by providing a consistent monitoring framework for water and soil indicators across seasons and regions.

## **6. Climate Variability and Adaptation Assessment Framework**

Beyond the baseline (historical) analyses, the DT-Agro workflow provides a ready framework for climate-scenario and adaptation assessments. The same processing chain that generates forcing for 1971–2024 can ingest alternative meteorological datasets (e.g., bias-corrected climate projections) and quantify resulting changes in dryness, ET demand, irrigation requirements and runoff response.

Future work will refine attribution of trends by incorporating time-varying crop patterns from multi-year IACS data and by integrating additional EO and in-situ information for calibration/validation (e.g., Sentinel-based soil moisture and actual ET products, IoT networks). This will enable more robust separation of climate signals from land-use and management changes.

In summary, D5.2 demonstrates that the DT-Agro Digital Twin can already quantify the observed range of hydroclimatic variability and its implications for agricultural water demand in Greece, and it establishes the methodological basis for systematic climate-change impact assessments and evaluation of adaptation/mitigation strategies.

## **7. Conclusions**

This deliverable synthesises the analytical outputs of the DT-Agro framework to describe the functioning of the Greek Agro-Hydro-System and the associated water, soil and environmental issues. It builds on the final national-scale DT-Agro application (daily simulations for 1971–2024, analyses mainly for 1974–2024) and the open spatial database of outputs provided in D4.3.

The results confirm the dominant west–east precipitation gradient and the corresponding patterns of climatic dryness and ETo. Across most agricultural regions, evapotranspiration dominates the water balance, while direct runoff becomes more relevant in the humid west, mountainous headwaters and locations with elevated imperviousness. EO-driven vegetation

indicators provide dynamic representation of crop water demand and support interpretation of seasonal variability.

National irrigation-demand estimates show strong inter-annual variability: dry years can require ~25–30% higher abstractions than wet years, and exceedance-probability analysis supports a risk-informed approach to drought preparedness and infrastructure planning. Relationships between irrigation requirements, climatic dryness and soil water-holding capacity provide a quantitative basis for targeted adaptation strategies.

Finally, DT-Agro establishes a consistent monitoring framework to evaluate mitigation and adaptation options (irrigation modernisation, soil-health practices, crop/management adaptation and nature-based runoff controls) and to track their impacts using spatially explicit indicators. The open DT-Agro portal enables reuse of the output datasets by researchers and stakeholders and supports transparent decision-making.

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