E-HYDRO: A Basin-Scale Digital Twin Framework for Integrated and Sustainable Water Cycle Management

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Abstract

Water resources management requires integrated digital tools capable of combining heterogeneous data, advanced models, and interactive visualization environments to support decision-making at basin scale. This paper presents the E-HYDRO platform, a basin-scale digital twin developed to improve the analysis, modelling, and management of water resources, with an initial implementation focused on the Guadiana River Basin in Spain. The platform acts as a digital representation of the basin by integrating geospatial information, satellite imagery, in-situ monitoring data, hydrometeorological records, terrain models, river morphology data, and outputs from hydrological, hydraulic, environmental, and artificial intelligence models. These data sources are processed and harmonized to provide a common operational environment where different components of the hydrological system can be analyzed jointly. The digital twin includes several analytical capabilities, such as satellite-based monitoring of surface-water bodies, estimation of groundwater-related indicators using remote sensing and piezometric data, assessment of hydrological recharge, flood-risk analysis, short-term water availability forecasting, water-quality monitoring, land-use classification, detection of environmental changes, and identification of critical areas. These models and indicators are integrated into an interactive WebGIS environment, allowing users to explore spatial patterns, temporal trends, monitoring points, and simulation outputs in a unified interface. From a platform perspective, E-HYDRO follows a modular and scalable architecture that supports data ingestion, model integration, storage, visualization, and future extensions. The first implementation demonstrates the potential of the digital twin approach to combine monitoring data, predictive models, and geospatial analysis tools, providing a decision-support framework for flood prevention, drought assessment, groundwater management, water-quality evaluation, and sustainable planning of water resources.

Keywords: Digital Twin, GIS, Hydrological Modelling, Water Resources Management.

1. Introduction

Water resources management is increasingly challenged by climate variability, changes in precipitation patterns, rising temperatures, growing water demand, and the higher frequency of extreme events such as floods and droughts [1,2]. These pressures are particularly relevant in Mediterranean and semi-arid regions, where water availability is highly variable and strongly influenced by seasonal dynamics, groundwater dependence, agricultural demand, and reservoir operation [1,3]. The increase in temperature associated with climate change contributes to greater evapotranspiration and higher irrigation requirements. At the same time, changes in rainfall distribution affect river flows, aquifer recharge, reservoir storage, and the availability of surface-water resources [1,2]. In parallel, water-quality problems are becoming more frequent due to nutrient enrichment, low-flow conditions, higher water temperatures, and the proliferation of algal blooms [4]. These combined effects require a transition from isolated modelling approaches towards integrated, adaptive, and data-driven management tools [5,6].

Hydrological, hydraulic, hydrogeological, and environmental models provide essential information for understanding the behavior of water systems [4,7]. However, these models are often developed independently, rely on different input datasets, and produce outputs in heterogeneous formats. This limits their practical use in operational decision-making, especially when water managers need to analyze multiple processes simultaneously, such as surface-water availability, groundwater recharge, flood risk, water quality, land-use evolution, and ecosystem condition [5,7]. Digital Twin (DT) technologies offer a suitable framework to overcome these limitations [8,9]. A DT can be understood as a dynamic virtual representation of a physical system, continuously updated through data, models, and analytical tools [8,9]. In the context of water resources management, a basin-scale DT can combine monitoring networks, satellite observations, geospatial information, terrain models, historical records, and predictive simulations within a single operational environment [9,10].

The E-HYDRO project addresses this challenge through the development of an intelligent platform for the modelling and virtualization of water resources. The platform is designed to integrate heterogeneous data sources and advanced analytical models to support the management of river basins. The initial implementation is focused on the Guadiana River Basin in Spain, which represents a relevant case study due to its water scarcity issues, groundwater dependence, environmental sensitivity, and exposure to hydrological extremes. This paper presents the design and first implementation of the E-HYDRO DT platform. The contribution focuses on the functional role of the platform as an integrated analysis environment, the main datasets and models incorporated, the general architecture supporting the DT, and the preliminary results obtained through the WebGIS interface and model visualization tools. The objective is to demonstrate how the platform can support decision-making by combining monitoring data, remote sensing, hydrological modelling, artificial intelligence, and interactive visualization at basin scale.

2. Conceptual Framework of the E-HYDRO DT

The E-HYDRO platform has been conceived as a DT of a river-basin system. Its objective is not only to store or display information, but to provide an integrated digital environment where the physical behavior of the basin can be analyzed through different data sources, models, indicators, and simulation outputs. The DT works through four main functional layers:

a. Data acquisition and integration: The platform incorporates information from multiple sources, including satellite imagery, hydrometeorological stations, in-situ monitoring, geospatial databases, LiDAR surveys, bathymetric data, orthophotos, terrain models, and outputs generated by project partners.
b. Data harmonization and structuring: The different datasets are processed and organized according to a common characterization framework. This includes the identification of the data owner, data provider, integration method, storage requirements, update

frequency, format, physical variable, and visualization needs. This step ensures that information can be correctly interpreted and reused by the platform.

c. Model and indicator integration: Hydrological, hydraulic, hydrogeological, environmental, and artificial intelligence (AI) models are incorporated into the platform either as direct model outputs, service-based modules, or interactive widgets. This enables the DT to represent different components of the hydrological cycle and their interaction with land use, climate, water quality, and river morphology.

d. Visualization and decision support: The results are displayed through an interactive WebGIS environment, dashboards, temporal plots, spatial layers, and 3D visualization tools. This allows users to explore the current state of the basin, analyze historical trends, evaluate model outputs, and compare alternative scenarios.

In this way, the E-HYDRO DT provides a structured connection between the physical basin and its virtual representation. Static datasets, such as digital terrain models or cartographic layers, provide the spatial foundation of the twin. Dynamic datasets, such as hydrometeorological records or monitoring data, allow the system to be periodically updated. Analytical models transform these data into indicators and predictions, while the WebGIS interface enables users to interpret the information spatially and temporally

Figure 1. General concept of the E-HYDRO DT: integration of monitoring data, remote sensing, geospatial information, hydrological models, environmental indicators, and visualization tools within a common basin-scale platform.

3. Data Sources and Integration Strategy

The E-HYDRO platform is based on the integration of heterogeneous datasets generated or provided by different partners and external sources. The specification document of the platform establishes a structured characterization process for each dataset, including its identification, data owner, data provider, integration protocol, storage needs, format, physical variable, unit, update frequency, and expected use within the platform. The main data categories considered in the platform are:

- Hydrometeorological data, including precipitation, temperature, wind, river flow, reservoir volume, and other variables obtained from monitoring networks.
- Geospatial and cartographic data, including basin boundaries, river networks, flood-risk areas, digital terrain models, orthophotos, land-use layers, and OpenStreetMap base maps.
- Remote-sensing products, including Sentinel-1 and Sentinel-2 imagery, NDVI, NDWI, water masks, surface-water extent, vegetation indicators, and radar-based information.
- Geomatics and 3D data, including LiDAR point clouds, drone imagery, bathymetric surveys, digital terrain models, and river morphology products.
- Water-quality data, including field campaigns, physicochemical parameters, nutrients, chlorophyll-a, and indicators related to eutrophication or harmful algal blooms.
- Model outputs, including flood simulations, water availability indicators, groundwater recharge, land-use classification, environmental change detection, and groundwater-related indicators.

The integration strategy depends on the characteristics of each dataset. Static or low-frequency datasets can be uploaded directly into the platform and stored as files, geospatial layers, or structured database records. Dynamic data, such as hydrometeorological or monitoring information, can be accessed through APIs or real-time data management mechanisms. Large geospatial datasets, such as point clouds or raster products, require dedicated storage and visualization services to ensure efficient access. A relevant aspect of the E-HYDRO DT is that not all datasets need to have the same update frequency. Some layers, such as orthophotos, LiDAR products, or digital terrain models, provide a stable geometric reference and may be updated only when new surveys are available. Other data, such as satellite observations, can be updated more frequently. This data integration strategy allows the platform to provide a coherent representation of the basin, while preserving the specific nature and update logic of each data source.

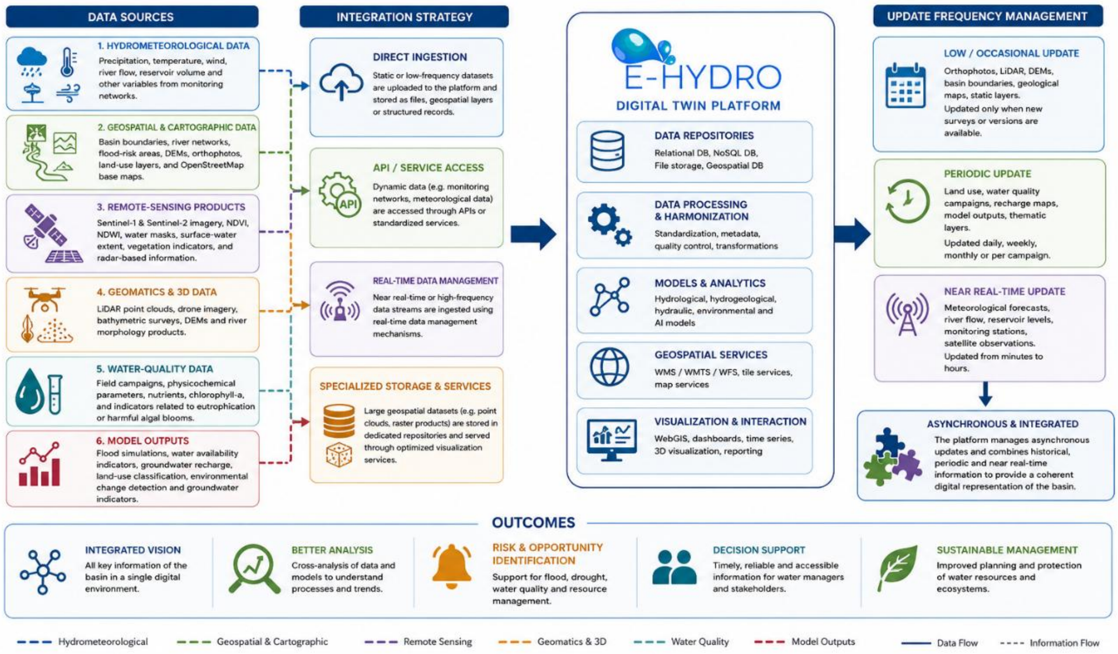

Figure 2. E-HYDRO data sources, integration workflows, and update strategy.

4. Main Analytical Components Integrated in the Platform

The main added value of the E-HYDRO DT lies in the integration of multiple analytical components within a common operational environment. These components cover different aspects of water resources management, from surface-water monitoring to groundwater assessment, flood risk, water quality, land use, and environmental change (see Fig. 3).

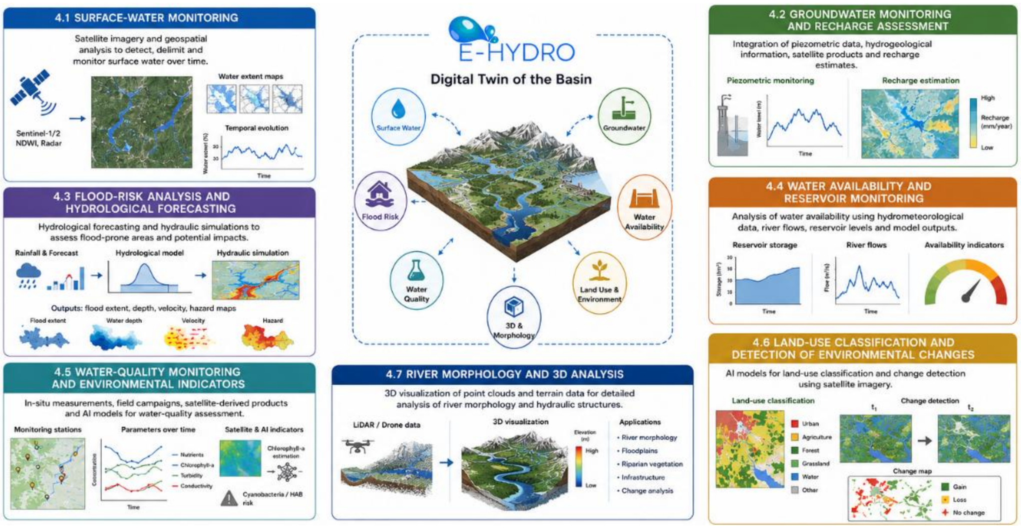

Figure 3. E-HYDRO platform architecture: interaction between the frontend, backend services, persistence layer, model integration, geospatial services, 3D visualization services, and dynamic data components.

4.1 Surface-Water Monitoring

Surface-water monitoring is one of the core functionalities of the platform. It is based on the use of satellite imagery and geospatial analysis to detect, delimit, and monitor water bodies over time. The system can use spectral indices such as NDWI, radar information from Sentinel-1, and image-processing algorithms to identify surface-water areas. The outputs include spatial layers representing water bodies and temporal graphs showing the evolution of water extent. This allows users to assess seasonal variability, identify persistent changes, and detect anomalies associated with drought, reservoir operation, or hydrological alterations. Within the WebGIS environment, users can select specific areas of interest, visualize water masks over base maps or satellite images, and compare the evolution of surface-water extent across different dates.

4.2 Groundwater Monitoring and Recharge Assessment

Groundwater is a key component in the Guadiana River Basin. The platform incorporates groundwater-related indicators through the integration of piezometric data, hydrogeological information, recharge estimates, and satellite-based products. One of the analytical capabilities considered in E-HYDRO is the use of satellite radar information to analyze ground deformation patterns that may be related to changes in groundwater levels. These indicators can be combined with piezometric measurements and hydrogeological models to support the interpretation of groundwater dynamics. In addition, the platform integrates spatially distributed recharge estimates derived from hydrological modelling. These outputs allow users to analyze recharge variability across the basin and relate it to precipitation patterns, land-surface characteristics, aquifer behavior, and observed groundwater conditions. The combination of monitoring points, recharge maps, and time-series visualization supports a more complete interpretation of groundwater status and evolution.

4.3 Flood-Risk Analysis and Hydrological Forecasting

Flood-risk analysis is another major functionality of the platform. The DT incorporates workflows related to hydrological forecasting and hydraulic simulation. These tools are designed to support the assessment of flood-prone areas and the potential impact of extreme rainfall events. The platform considers the use of hydrological methods to estimate runoff and hydrographs based on precipitation data and short-term weather forecasts. These results can be used as input for hydraulic simulations in critical areas, generating spatial outputs such as flood extent, water depth, velocity, and hazard maps. In the WebGIS interface, these outputs can be visualized as thematic layers, allowing users to identify areas potentially affected by flooding and to support preventive decision-making. This functionality is especially relevant for basin authorities, civil protection, and infrastructure managers.

4.4 Water Availability and Reservoir Monitoring

The platform also supports the analysis of water availability through the integration of hydrometeorological data, river-flow information, reservoir levels, and model-based indicators. These data allow users to evaluate the current and expected availability of water resources at different spatial scales. The DT can display reservoir storage evolution, river-flow trends, and short-term projections based on hydrological modelling. These functionalities are intended to support the analysis of drought conditions, water allocation, reservoir operation, and the planning of water resources under changing climatic conditions. By combining monitoring data and model outputs, the platform provides a basis for assessing the evolution of available water volumes and identifying potential situations of scarcity.

4.5 Water-Quality Monitoring and Environmental Indicators

Water quality is addressed through the integration of in-situ measurements, field campaigns, satellite-derived products, and artificial intelligence models. The platform considers indicators related to nutrients, chlorophyll-a, eutrophication processes, and harmful algal blooms. One of the analytical lines focuses on the estimation of chlorophyll-a concentration using satellite imagery and deep-learning models. This allows the spatial monitoring of water-quality conditions in reservoirs and water bodies. Another line addresses the detection of cyanobacteria or harmful algal bloom risk through the combination of in-situ sensor data and multispectral satellite information. The platform also enables the visualization of water-quality monitoring stations and the temporal evolution of selected physicochemical parameters. This makes it possible to identify trends, anomalies, and areas requiring further investigation.

4.6 Land-Use Classification and Detection of Environmental Changes

Land use and land-cover dynamics are relevant for understanding hydrological processes, erosion, runoff generation, water quality, and ecosystem degradation. The E-HYDRO platform integrates artificial intelligence models for land-use classification based on satellite imagery. These models can segment images into different land-use categories and quantify the percentage of each class in a selected area. By comparing results across time, the platform can support the detection of land-use changes, identification of critical areas, and analysis of environmental degradation processes. This functionality is particularly useful for assessing the relationship between land-use transformation and water-related impacts, such as increased runoff, reduced infiltration, nutrient input, or ecosystem stress.

4.7 River Morphology and 3D Analysis

The platform includes 3D visualization tools for point clouds and terrain products. These datasets are essential for analyzing river morphology, floodplains, channels, riparian vegetation, embankments, and hydraulic structures. LiDAR and photogrammetric products can be visualized through web-based point-cloud viewers, enabling users to inspect river sections, terrain characteristics, and spatial features directly in the platform. In addition, classified point clouds and derived products can support the analysis of vegetation structure, riverbank condition, and changes in fluvial environments.

5. General Platform Architecture

Although the main focus of E-HYDRO is the integration of water-related analyses within a digital twin environment, the platform requires a robust architecture to support data ingestion, storage, processing, model integration, visualization, and user interaction. The architecture follows a modular and service-oriented approach. This means that the platform is organized into independent components that can be deployed, maintained, updated, and scaled separately. The main architectural blocks are the frontend interface, backend services, data storage layer, geospatial services, 3D visualization services, model integration layer, and dynamic data components.

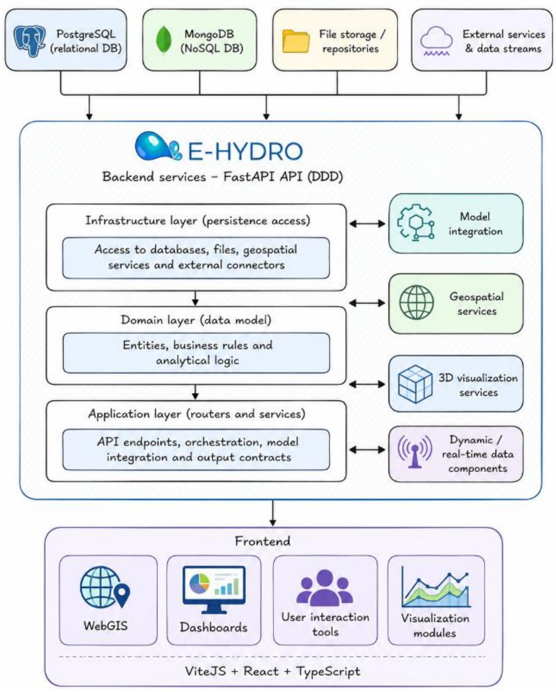

Figure 4. General architecture of the E-HYDRO platform, showing the interaction between the frontend, backend services, persistence layer, model integration, geospatial services, 3D visualization services, and dynamic data components.

The frontend interface provides the WebGIS, dashboards, user interaction tools, and visualization modules. The backend services expose platform functionalities through APIs and connect the frontend with databases, files, models, and external services. The data storage layer combines relational databases for structured information, non-relational databases for flexible and semi-structured data, and file repositories for large geospatial products. The geospatial services manage raster and vector layers, base maps, satellite products, and spatial outputs from models. The 3D visualization services support the rendering of LiDAR point clouds and other three-dimensional datasets. The model integration layer enables the incorporation of model outputs, analytical tools, and interactive widgets. Finally, real-time or dynamic data components can support the ingestion and management of monitoring or sensor-based information. This architecture allows the platform to evolve progressively as new models, datasets, or functionalities become available. It also supports the future transfer of the digital twin framework to other river basins.

6. Results and discussion

The first implementation of the E-HYDRO platform demonstrates the feasibility of integrating heterogeneous data and analytical outputs within a common WebGIS-based digital twin environment. The current implementation focuses on the Guadiana River Basin and includes several visualization and analysis modules. The WebGIS interface allows users to explore the basin boundary, pilot areas, monitoring points, and thematic layers over different base maps. It provides tools for visualizing geospatial information, model outputs, and temporal indicators. The platform has also been prepared to integrate specific widgets corresponding to the analytical models developed in the project. The preliminary implementation of the E-HYDRO platform demonstrates its capacity to integrate heterogeneous datasets, analytical models, and visualization tools within a common digital twin environment. The current version, focused on the Guadiana River Basin, provides an interactive WebGIS interface where users can explore spatial layers, monitoring points, model outputs, and environmental indicators.

The general interface of the platform allows the visualization of the basin boundary over a cartographic base map, together with access to different management modules, including surface-water quality, groundwater quality, precipitation, vegetation models, and hydrological models. This configuration provides a unified access point to the main information layers and analytical components of the digital twin.

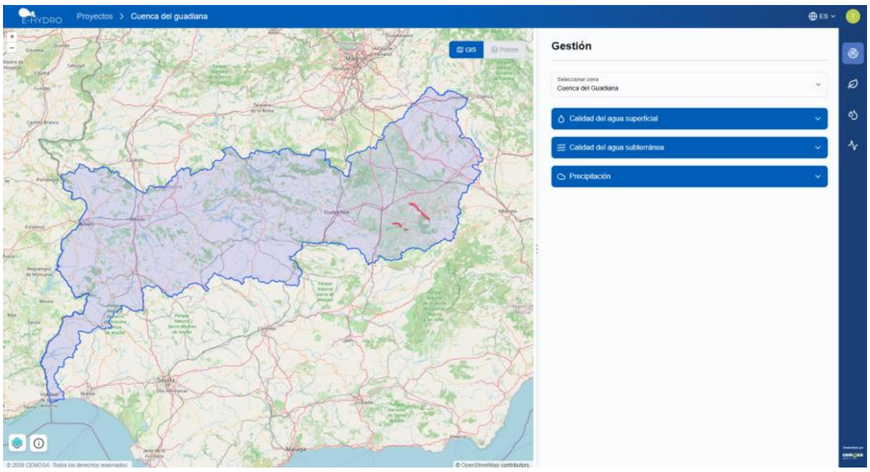

Figure 5. E-HYDRO platform: general WebGIS interface showing the Guadiana River Basin and the main management modules.

One of the implemented functionalities is the visualization of water-quality monitoring data. Monitoring stations are represented spatially within the basin, while the side panel provides access to temporal plots and spatial analyses of selected physicochemical parameters. This enables the identification of trends, anomalies, and spatial patterns related to water-quality evolution.

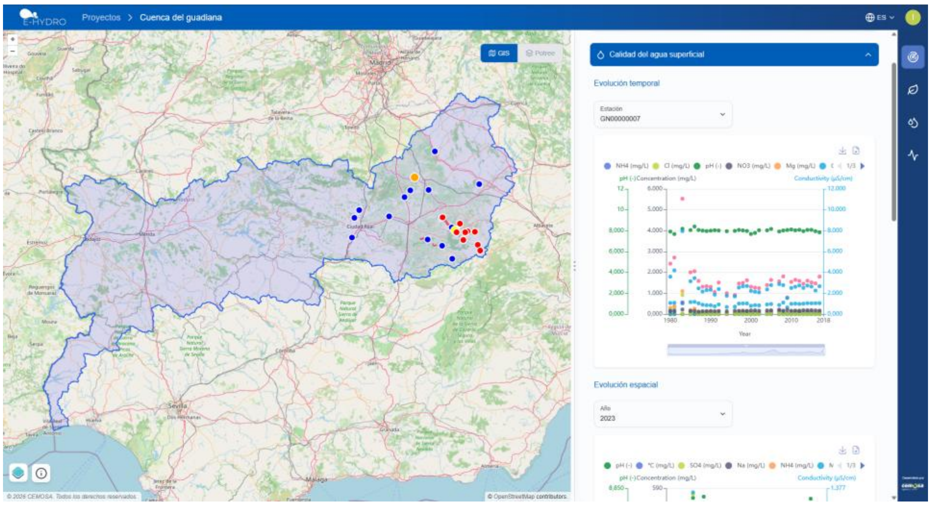

Figure 6. E-HYDRO platform: water-quality monitoring module with monitoring stations and temporal evolution of selected parameters.

The precipitation module allows users to analyze historical rainfall records from selected monitoring stations. Annual precipitation values and accumulated summaries over different time windows provide a useful basis for assessing hydrometeorological variability and supporting drought-related analyses.

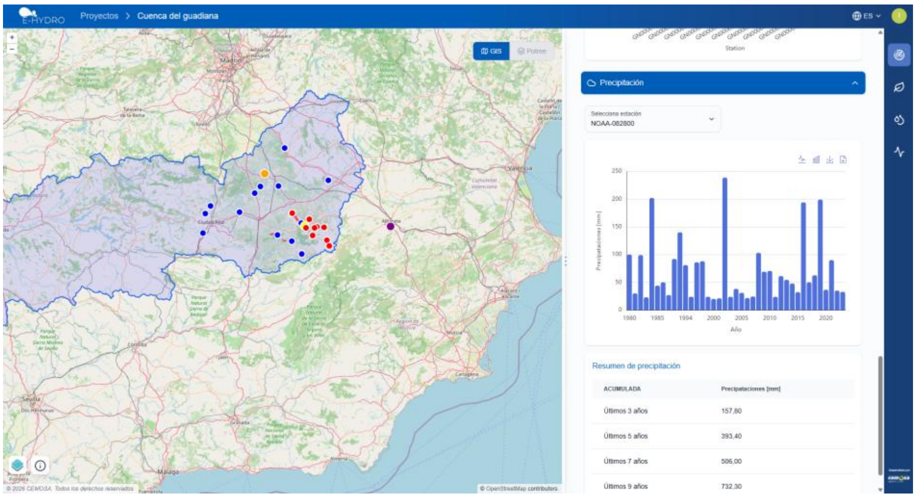

Figure 7. E-HYDRO platform: precipitation monitoring module showing annual rainfall records and accumulated precipitation summaries.

The platform also includes vegetation and land-use analysis tools. The 3D point-cloud viewer allows users to visualize classified LiDAR data, including ground, water, vegetation, buildings, and other classes. This functionality supports the analysis of river morphology, riparian vegetation, and terrain characteristics.

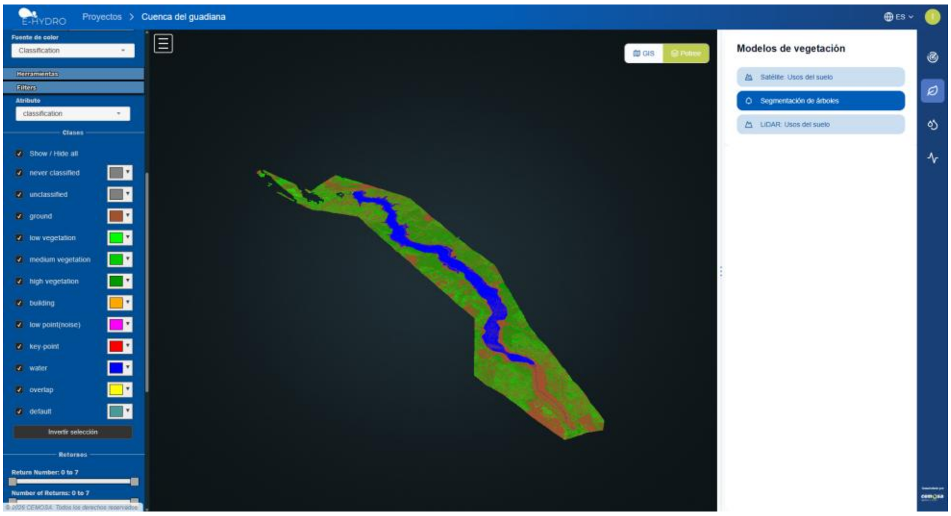

Figure 8. E-HYDRO platform: 3D point-cloud visualization and vegetation classification module.

In addition, the land-use module enables the visualization of satellite-based classification results and graphical summaries of land-cover distribution in selected areas. This supports the assessment of land-use dynamics and their potential influence on hydrological and environmental processes.

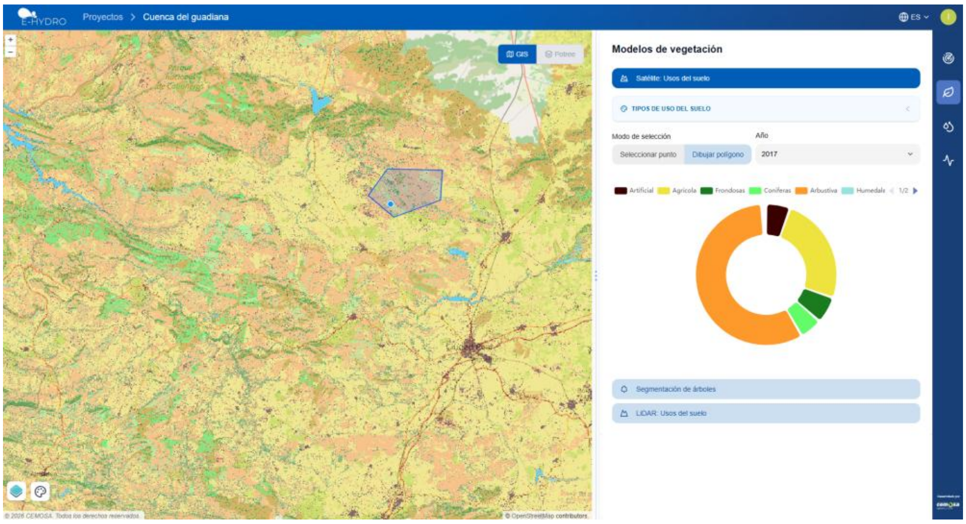

Figure 9. E-HYDRO platform: land-use classification module with spatial land-cover information and class distribution.

Hydrological model outputs are also integrated into the platform. The hydrological model's module includes tools for groundwater monitoring, surface-water monitoring, meteorological forecast-based projections, IDF curve generation, and hydrological balance analysis. The visualization of recharge, irrigation demand, and overexploitation indicators supports the assessment of groundwater and surface-water interactions.

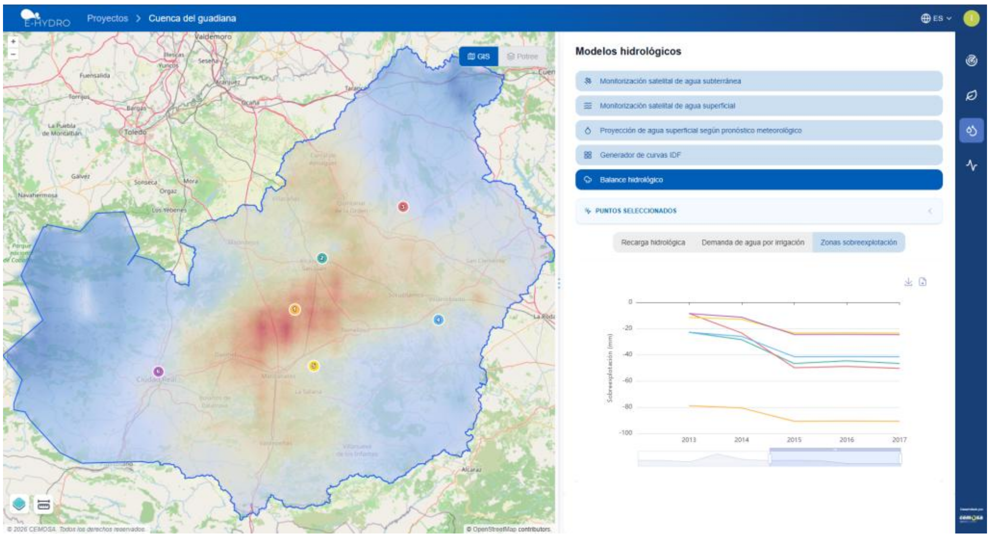

Figure 10. E-HYDRO platform: hydrological modelling module showing hydrological balance indicators and temporal evolution of selected variables.

Overall, these results show that the E-HYDRO platform provides a practical digital twin environment for integrated basin-scale analysis. By combining WebGIS visualization, monitoring data, satellite products, 3D information, and model outputs, the platform supports the interpretation of hydrological and environmental processes. The modular structure of the system also facilitates the progressive incorporation of new datasets, analytical tools, and decision-support functionalities. The current implementation confirms the potential of the platform to support water-resources management in the Guadiana River Basin. In particular, it enables the joint analysis of water quality, precipitation, vegetation, land use, 3D river morphology, and hydrological indicators. Future developments will focus on increasing automation, improving model integration, incorporating additional real-time data sources, and expanding decision-support capabilities for drought assessment, flood prevention, groundwater management, and environmental monitoring.

7. Conclusions

This paper presented the E-HYDRO platform, a basin-scale Digital Twin framework for integrated water resources management. The platform combines heterogeneous data sources, monitoring information, satellite products, hydrological and environmental models, and visualization tools within a common WebGIS-based environment. The first implementation in the Guadiana River Basin demonstrates the feasibility of integrating spatial and temporal information to support the analysis of water quality, precipitation, vegetation, land use, groundwater indicators, hydrological balance, and 3D river morphology. This confirms the potential of the platform to provide a unified view of key water-related processes at basin scale.

The modular architecture of E-HYDRO enables the progressive incorporation of new datasets, models, and analytical services, making the platform scalable and transferable to other river basins. Overall, the results show that E-HYDRO can support decision-making for drought assessment, flood prevention, groundwater management, water-quality evaluation, and sustainable basin planning.

Future work will focus on feeding and updating the integrated models with new monitoring data, improving the connection between model outputs and operational indicators, and supporting decision-making for more efficient and sustainable water resources management.

8. Acknowledgements

This work was supported by the R&D&I TransMisiones 2023 programme, jointly managed by CDTI Innovation and the Spanish State Research Agency, through the research project E-HYDRO: Development of an Intelligent Platform for the Modelling and Virtualization of Water Resources.

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