A Web GIS platform for critical infrastructure monitoring within "PROION" project

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ABSTRACT

To ensure the sustainability of critical infrastructures, such as public infrastructure, dams, bridges, etc., a holistic monitoring approach is required. With regard to this, European Union (EU) and the Hellenic government are financially supporting a project for the multiparametric monitoring of the Enceladus Hellenic Supersite (EHS), entitled "PROION". A building on the Patras University campus, a dam, and an active landslide within the EHS area constitute the three main case studies of the project and are being monitored using Remote Sensing (RS) and in-situ instrumentation. InSAR data, GNSS and micro-accelerometer measurements are collected and evaluated with reference to 3D point clouds, developed from TLS and UAV. In addition, fuzzy logic networks (FLN) methods and machine learning (ML) algorithms are applied for the final control of the data and decision-making support. A web-based Geographic Information System (Web GIS) platform is designed and developed in order to concentrate and disseminate the diverse and multidimensional data and methodology outcomes of "PROION". Modern web architecture frameworks, and geo-visualization technologies (e.g., SaaS, React JS, Flask, WebGL, Mapbox GL JS, etc.) are combined into a robust Web GIS platform, providing an augmented end-user interaction and enhanced geospatial tools through a 4D web map environment. Furthermore, big data spatiotemporal analysis, geospatial data overlaying/fusion, and near real-time earthquake events feed are included, achieving the optimal monitoring of high-priority infrastructures.

Keywords: critical infrastructure, monitoring, remote sensing, soft computing, Web GIS, spatiotemporal analysis

1. INTRODUCTION

The need for the development of reliable cost-effective systems for monitoring engineering infrastructure is increasing, especially considering the effects of ageing and the impact of natural hazards[1]. According to the same study, a rapid increase in publications, associated with remote sensing (GNSS, SAR, LiDAR and UAV) sensors for infrastructure monitoring, has been noticed in the last decade (2012–2022). Many public organizations and private companies are developing Web GIS applications, proving that such applications incorporating real-time data, archive data and prediction models can be a smart powerful tool providing useful information and supporting decision making by the local stakeholders.

The evolution of Web GIS has been steady, progressing in tandem with the growth of the internet and the advancement of hardware and software. Web GIS has revolutionary effects like interactive access to geospatial data, real-time data integration and transmission, and access to platform-independent GIS analysis tools[2,3]. The web provides the end user with the ability to interact with the data and make better decisions from it.

A review study about Web GIS methodologies was presented stating the development of Web GIS platforms, and giving future recommendations[4]. In that study authors mention that the basic architecture of a Web GIS platform is the client-server architecture; this is because the standard of geo-data is very specific in the sense that it requires a map server on top of the web server and a database compliant with geo-data, while most other websites do not require these extra technologies to function properly[5].

Many studies have been published the previous years about Web GIS applications in diverse domains. A Web GIS was developed for the visualization of the results of a dynamic finite element analysis applied to the calculation of seismic risk on constructions belonging to the Italian infrastructural heritage, specifically bridges, viaducts and overpasses[6]. In another work[7], a framework combining GIS processing, Multi-Criteria Analysis calculation, Relational Database Management System server remote implementation, and Web GIS online visualization was developed. The specific system allows to choose the localization of a new Power to Gas plant in the territory of Sicily and to visualize it on Web GIS. In a study focusing on assessing and monitoring the response of critical infrastructures (bridges and viaducts) when subjected to natural hazards, another Web GIS was designed[8]. The development of the Web GIS application for transport infrastructure management in the city of Serang was presented[9]. Authors mention that every data on the transport infrastructure could be gathered and stored on the web. Furthermore, every single transport planning should refer to this transport information system. The spatial analysis is then executed, e.g., where the planned bridges are located, how many bridges defect, the status of the road and where the road is located, etc.[9]. Other researchers[10] developed a Web GIS platform to assess the impact of "Low Impact Development" systems on mitigating urban flooding and to support their implementation at the urban catchment scale.

The utilization of Information and Communication Technology (ICT) as a digital infrastructure concerning disaster countermeasures in Japan, was described in another manuscript[11]. Specifically, the study introduced development cases of the systems integrating social media and Geographic Information Systems (GIS) and presented the utilization potential as a digital infrastructure[11]. A Web GIS application for online flood warnings in near real-time was designed and developed for the Vu Gia-Thu Bon River in Vietnam[12]. As the authors mentioned, the main purpose of this study is to develop an online flood warning system in real-time based on Internet-of-Things technologies, GIS, telecommunications, and modelling to support the local community in the vulnerable downstream areas in the event of heavy rainfall upstream[12]. Other researchers[13] presented a Web GIS application, focusing on helping the decision-makers in the state of New Jersey, USA, to access and understand relevant geographic information concerning sea level rise and exposure to coastal inundation.

2. PROION PROJECT

PROION project[14] carries out a critical infrastructure monitoring methodology based on remote sensing and in situ measurements. Three sites with very different characteristics in the Prefecture of Western Greece (Figure 1) were chosen for monitoring in the frame of PROION. A small village lying on an active landslide and two critical infrastructures, the building of the Geology Department at the University of Patras and a freshwater Dam called Asteri, are surveyed using data from SAR interferometry, GNSS and micro-accelerometer sensors. Additionally, TLS and UAV 3D point clouds are used as reference data.

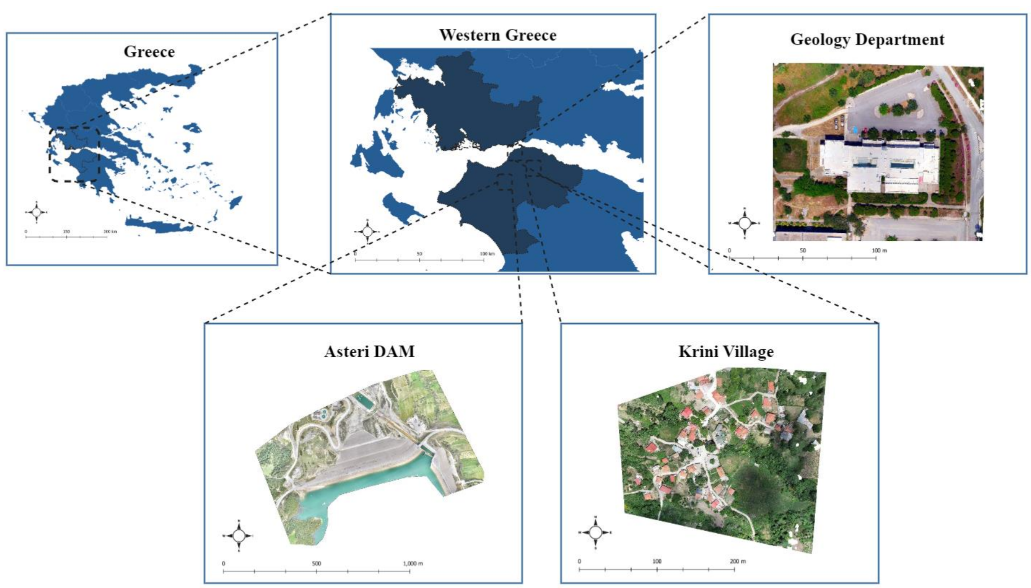

Figure 1. The three chosen sites for monitoring within the frame of the PROION project.

3. THE WEB GIS PLATFORM ARCHITECTURE

The generation of new spatial data as well as the acquisition of rich datasets within the scope of the project can provide limited information without the use of a modern GIS environment encompassing advanced spatial analysis tools. The development of a holistic framework for the monitoring of critical infrastructures constitutes a demanding task, considering the diversity of the datasets in terms of storage, handling and visualization. To overpass the potential limitations of this implementation and with the scope of developing a robust Web GIS platform, modern techniques and state-of-the-art technologies have been leveraged. The following sections provide a detailed description of the implemented platform considering it as a single solution, consisting of the back-end and the front-end components.

3.1 Datasets and database management

The introduced monitoring framework for critical infrastructures, integrates efficiently a great number of diverse datasets and technologies, aiming to provide a comprehensive solution with augmented capabilities and tools. To this end, GNSS and micro-accelerometer measurements, InSAR data, UAV and TLS high-resolution 3D point clouds are produced and integrated, as well as fuzzy logic networks (FLN) methods are applied. Combining the aforementioned datasets and methods, detailed knowledge of geomorphology and the temporal land movements of each case study site can be obtained. Supportively to these datasets, data from external official sources are utilized (i.e., earthquake events feeds, geological maps, meteorological stations) and integrated into the overall framework.

The importance of having a central solution for the integration of the different dynamically produced spatiotemporal datasets led to the development of a server machine that encompasses all the data creation and acquisition procedures, as well as their storage into a relational database with spatiotemporal management query capabilities. For these purposes, a PostgreSQL13 relational database with the PostGIS extension has been deployed as the central consolidated data storage solution. The implemented database schema provides an optimal relation storage structure that enables the ability of complex spatiotemporal queries. The following Figure 2 demonstrates the implemented database schema of the PROION project.

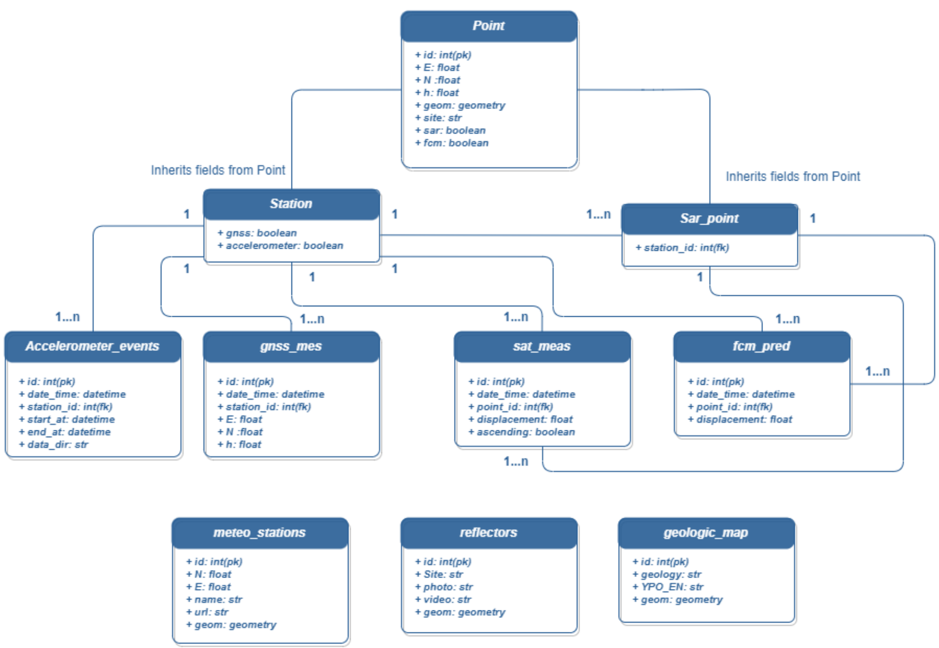

Figure 2. The UML diagram of the database schema of the PROION project.

3.2 General structure

To leverage the valuable-produced and concentrated knowledge of the PROION project a novel GIS environment constituted the best solution[15]. To this end, a Web GIS platform is developed as a Software-as-a-Service (SaaS) web application[16] consisting of two integral components, the back-end and the front-end which together form the software application. More specifically, the back-end is responsible for handling data processing and communication with the various datasets, while the front-end provides the user interface and ensures a seamless user experience. Regarding the former, a reliable and stable communication path is established between the user's interface and the offered datasets, able to handle complex multiparametric requests. On the other hand, strictly interconnected with the back-end component, the front-end user interface (UI) is developed following fundamental principles of user experiences (UX)[17] integrating advanced web tools for spatiotemporal data handling and visualization, enhancing the monitoring of critical infrastructures.

The optimal performance of the Web GIS platform is strongly dependent both on the user's interface and the established interconnection with the offered data of the PROION project. Thus, each of its components must be developed in a manner that ensures the successful and continuous operation of the whole system. Taking into consideration the main purposes of the described platform the development needs to follow an agile architecture that makes it feasible to manage the monitoring of big-scale infrastructures. For instance, a large-scale scenario entails the existence of a denser network of monitoring stations and the generation of a significantly bigger amount of data. Depending on that, the architecture of the Web GIS platform is designed to be adaptable to different spatial scales and needs.

Aiming towards it, an advanced back-end component is developed to efficiently handle HTTP requests, trigger different functions corresponding to dedicated requests and return a well-structured response backwards to the user's interface. Simultaneously, the front-end component is functionalized to handle and visualize multidimensional spatiotemporal dynamic content data. Considering the above, the nature of the introduced platform requires the use of an optimal combination of modern web-based technologies and powerful programming languages, capable to construct a high-performance software product. Figure 3 illustrates the diagram of the architecture of the PROION Web GIS platform.

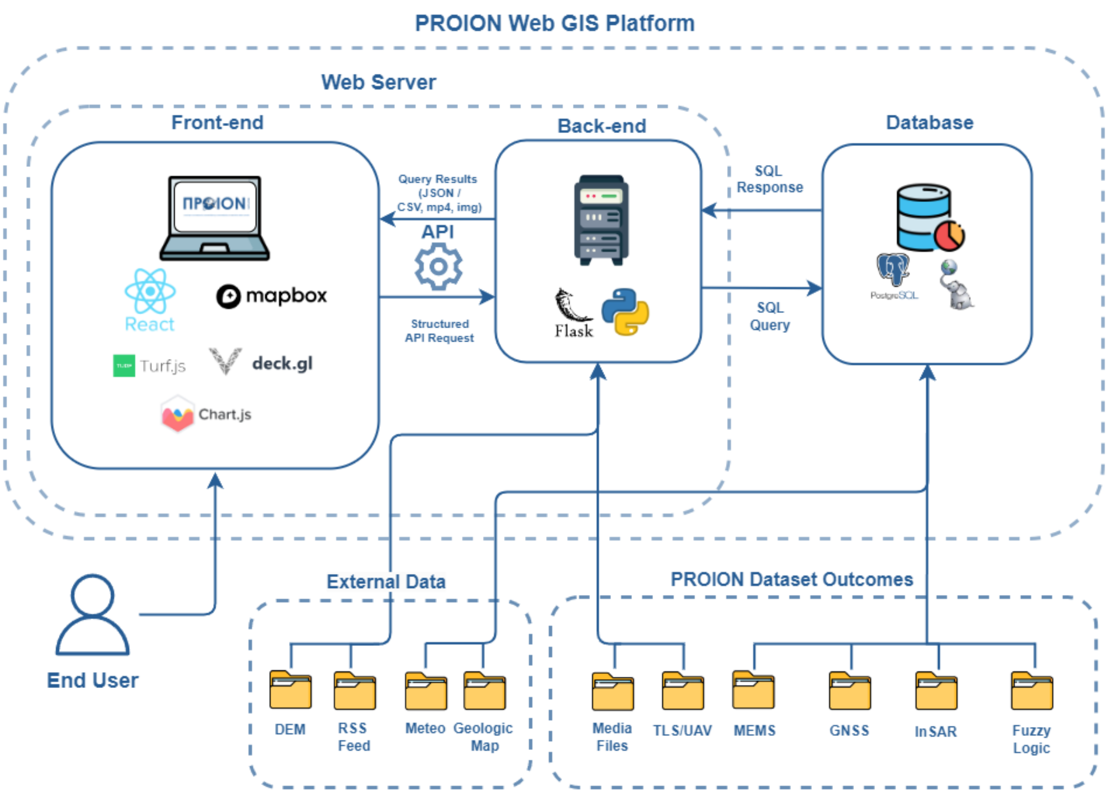

Figure 3. Diagram of the general architecture of the PROION Web GIS platform.

4. THE WEB SERVER IMPLEMENTATION

The web server constitutes integral part of the back-end component for the establishment of end-to-end communication between the offered data and the user interface. This communication is provided by developing an advanced Application Programming Interface (API) written entirely in the high-level general-purpose programming language Python3, combined with the microweb framework Flask, which additionally provides a robust set of libraries dedicated to handling HTTP requests.

4.1 API implementation

The implemented requests are structured following the guidelines specified by open worldwide standards, such as OGC, giving the ability to parameterize them based on specific needs. These requests are separated into three categories based on the functionalities that are invoked for: 1) data retrieval from the database, 2) local or external data and media files serving, and 3) spatial data processing. In the case of data retrieval from the database, the Python libraries "SQLAlchemy" and "psycopg2" are utilized for structuring and handling the SQL queries, establishing a seamless connection between the Flask application and the database of the PROION project. As for both the data that are locally stored into the server (i.e., 3D point clouds and media files) and the data from external sources (i.e., earthquake events feeds) are served on demand with dedicated requests, utilizing the Flask file sharing functionalities and commonly used Python libraries, such as "requests" to execute "GET" requests for fetching data from external open sources. Lastly, given the Python interoperability of the Flask framework, it is feasible to integrate additional Python scripts into the web server, extending its capabilities for invoking internal spatial processes, and avoiding their execution to the front-end component that might yield the deterioration of the user's experience. Figure 4 depicts the use case diagram of the implemented API.

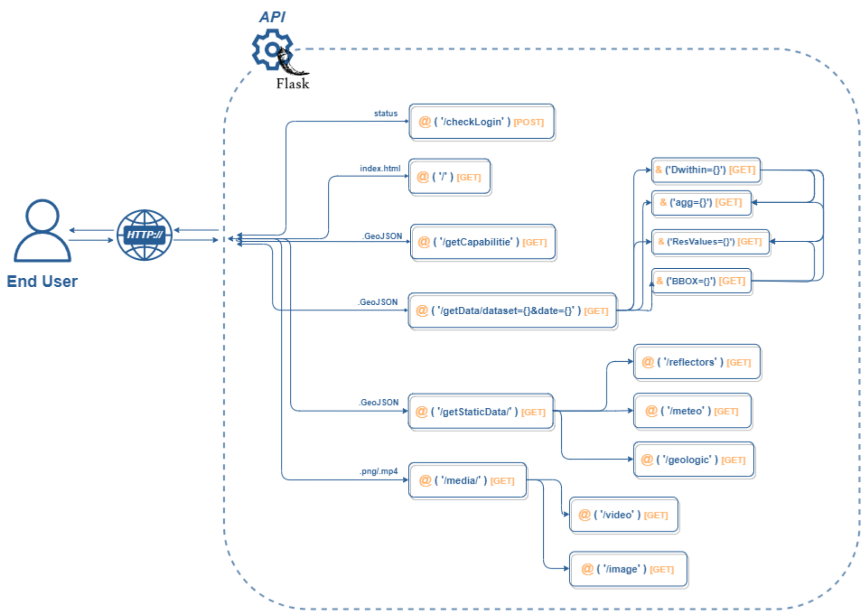

Figure 4. The use case diagram of the implemented API.

4.2 Web server's components intercommunication

The web server is also responsible for serving the front-end component of the Web GIS platform, giving the end user the ability to access it via an HTTP request to the primary web domain name of the platform. The front-end user interface consists of a plethora of interconnected files and is developed as a ReactJS application, applying the advanced functionalities of a state-of-the-art technological framework. Regarding the communication between the front-end and back-end, the "Axios" JavaScript library is used for sending asynchronous HTTP requests from the side of the front-end directly to the web servers, while also handling their responses, following the requests' structure that is defined by the API implementation. Each request corresponds to a specific app route of the Flask application based on the different kinds of responses. For instance, an individual route is responsible for data retrieving from the database and a different one for the stored media files.

Taking into consideration the complexity of the requests due to the multiparametric parameters-filters (e.g., time aggregation, values thresholds, spatial filters), the above approach is applied to ensure the successful and smooth operation of the web server's intercommunication, enhancing the overall reliability and performance of the web server and the API implementation, instead of relying upon a more complex structure that may yield to frequent operational errors.

5. THE ENHANCED USER INTERFACE

The user interface constitutes the web server's component through which the end-user interacts with the Web GIS platform and has access to the privileges of PROION's outcomes. Aiming to develop a web-based interface that provides all the required capabilities for successful monitoring of critical infrastructures, an efficient combination of web state-of-the-art technologies has been applied offering an augmented visualization and enhanced spatial processing tools. Considering that the majority of the data consumed by the platform constitutes the outcomes of a recurrent observation through time, the user interface must be developed in a manner that obtains their visualization and analysis, by providing all the needed tools and functionalities that enable an enhanced user experience.

5.1 Leveraged technologies

For achieving that, one of the most popular and advanced JavaScript libraries, "ReactJS", is used to build a modular, performant, and functional user interface with a virtual DOM and component-based architecture[18]. Moreover, the style sheet language CSS is used for styling adjustments, in order to create a user-friendly modern interface. In regard to the spatial visualization and analysis tools are developed mainly based on the functionalities offered by three spatial-oriented JavaScript libraries: Mapbox GL JS, Deck.gl and Turf.js, and the additional use of Chart JS for dynamic and interactive time series charts.

Mapbox GL JS is one of the most promising spatial libraries, creating a high-end virtual Earth 3D environment with advanced interactivity tools. Based on web technologies such as WebGL and Canvas, it boosts users' experience via a significantly less, compared to other alternatives, network bandwidth[19], as well as a large variety of 3D visualization capabilities (e.g., 3D map navigation, thematic basemaps, feature styling and extrusion, etc.), offering a smooth and high-end experience. Supportively to Mapbox GL JS, the Deck.gl is an open-source library, that provides the algorithmic links between the 3D data handling and its rendering on the map[20]. A great number of fine-tuned functionalities give the capabilities to upgrade the development of a Web GIS, reinforcing it with significantly useful and out-of-the-box data visualizations. The development of a Web GIS platform requires spatial tools that deal with the multidimensional substance of the spatially referenced information and the formats, to be created. In combination with functions developed from scratch, Turf.js an open-source library offering a wide variety of useful spatial-oriented functions[21], is utilized to enrich the algorithmic capabilities of the spatial analysis tools. The time dimension of the observed data consumed by the Web GIS requires additional tools dedicated to time series visualization, in order to achieve efficient monitoring of the integration process. To fulfill that need, an open-source lightweight library Chart JS is used, providing visually augmented dynamic and interactive charts with high parameterization capabilities regarding styling and interactivity[22].

5.2 Spatiotemporal functionalities and visualization techniques

By leveraging the above-mentioned technologies and libraries, the UI of PROION's Web GIS platform is developed and functionalized to handle successfully, parse efficiently and visualize properly all the data outcomes of the current project. The platform is developed as a monitoring site-based solution offering the ability to the end-user to parameterize their monitoring experience based on the preferable site, time period and datasets. More specifically, the end-user has to set a number of mandatory parameters-filters (i.e., Site, Observed Datasets, Time Period) and optionally apply some additional parameters-filters that specialize the dataset's time aggregation, result values and spatial extend. Regarding the latter, the platform gives the ability to draw on the displayed map either a bounding box (BBOX) or a circle (Distance) to specify the area of interest for the monitoring case. The following Figure 5 illustrates the "PROION Data Search Tab" which provides the capability to the end-user to apply parameters-filters, in order to efficiently determine the dedicated data requests based on the monitoring scenario.

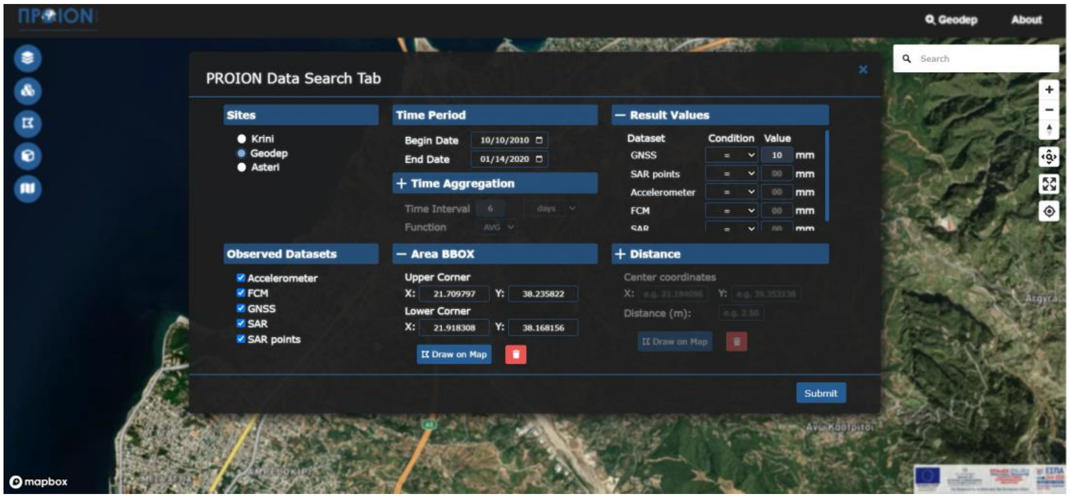

Figure 5. Illustration of the embedded "PROION Data Search Tab" for the Web GIS platform that enables the end-user to query the available datasets based on their needs.

The determination of end-user's parameters-filters is followed by the initialization of the map and the execution of data requests. The dynamic graphical interface enables the interaction of the end-user with the different data layers via the layers' panel, providing the ability to activate and deactivate them onto a 3D map environment provided by Mapbox GL JS. Each of these layers provides important information about its specific features, via map-embedded popup windows, enriching the end-user's knowledge through a holistic view of the monitoring area. Towards this direction, the live earthquake events of the last 48 hours, offered by the National Observatory of Athens (NOA), in combination with the micro-accelerometer measurements, provide essential near real-time information for the stability and seismic stress that the monitored critical infrastructure receives. Figure 6 depicts the end-user's capabilities of interaction and visualization with the provided datasets within the map environment.

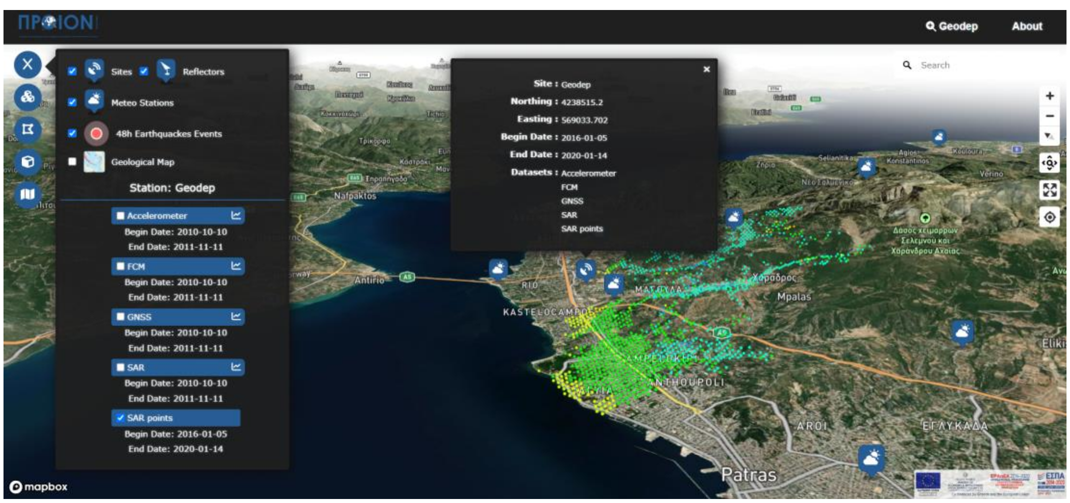

Figure 6. Illustration of the end-user's capabilities of interaction and visualization with the provided datasets onto the map environment.

Each site is characterized by specific geomorphological and environmental conditions, composing a unique monitoring case. The installation of GNSS stations and Radar Corner Reflectors aims for precise observation of the monitoring area through time, creating valuable information with high spatiotemporal granularity. In combination with the near-future predictions related to displacement values, calculated using fuzzy logic networks, the monitoring capabilities of the platform are beyond the present-time limitations. For the visualization and cross-analysis of these significant datasets, the Web GIS offers the ability of a time series correlation via interactive charts, rendered by the Chart JS library. The following Figure 7 depicts the time series of the GNSS and SAR observations as well as the corresponding FCM vertical predictions of the monitoring site of Patra's University Geology Department, visualized as a multidataset line chart.

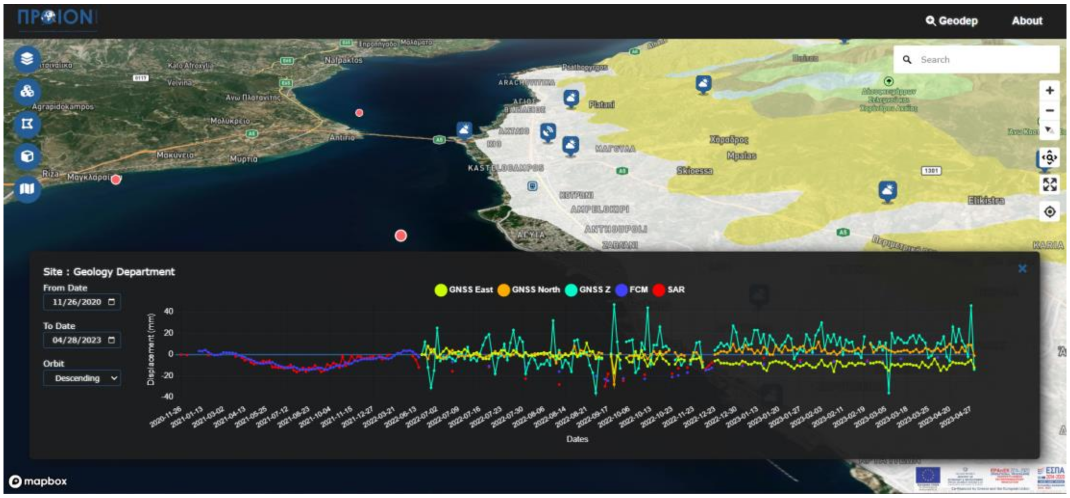

Figure 7. Time series of the GNSS, SAR observations and FCM vertical predictions of the monitoring site of Patra's University Geology Department, visualized as a multiline-dataset line chart.

For leveraging the maximum added value of the InSAR spatiotemporal observations, an advanced spatial tool was developed embodying functionalities of Turf.js, to provide the average displacement of a user-determined area, as well as to extract elevation and slope information via a back-end spatial process. The outputs of this tool are displayed on an interactive chart and are colorized based on the different computed average values, using a widely indicated color palette for the illustration of displacement measurements. Figure 8 shows an output of the aforementioned tool executed for a specified area at the Charadros River's end.

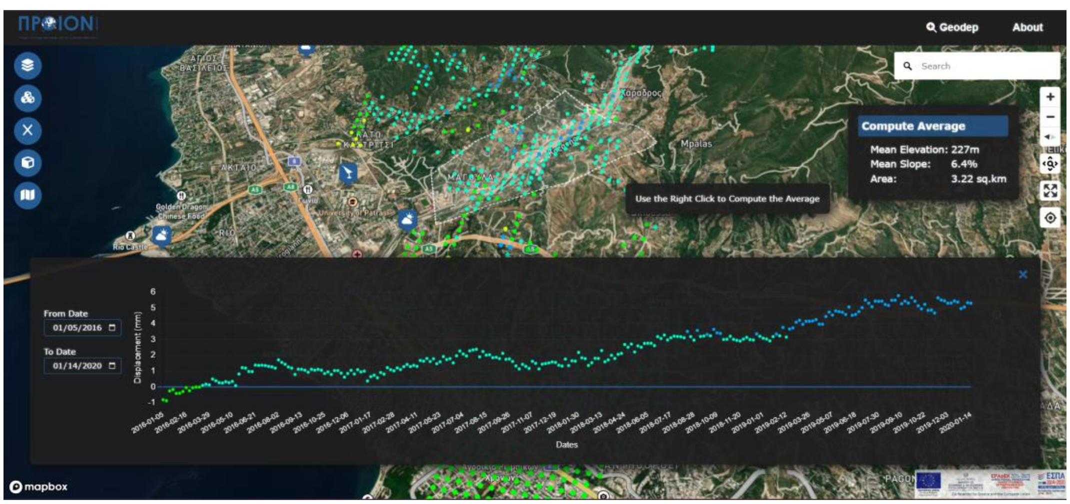

Figure 8. An example output of the "Compute Average" tool executed for a specified area at the Charadros River's end.

Furthermore, the most challenging data outcomes of the PROION project are the three individual 3D point clouds that are captured for each of the case study sites. Their proper integration in the Web GIS platform and their visualization required the optimal combination of the point-cloud resolution and their downloading payload. To address this challenge and cope with the limitations that yield from the big storage size of the datasets, a pre-process routine is determined for the reduction of their size via the optimal simplification of their spatial resolution, utilizing the "Shape Tools" QGIS Plugin written in Python. In continuation, in order to handle and visualize the 3D point clouds into the interactive map of the Web GIS platform, the Deck.gl class constructor "PointCloudLayer" is used to render them with 3D positions, normals and colors. For demonstrating purposes of the entire point clouds in their real captured spatial resolution, in addition to the map visualization, a demo video is offered for each point cloud accessible through a popup embedded window. Figure 9 illustrates the point cloud of the monitoring building of the Geology Department on the Patras University campus, rendered on the 3D map environment.

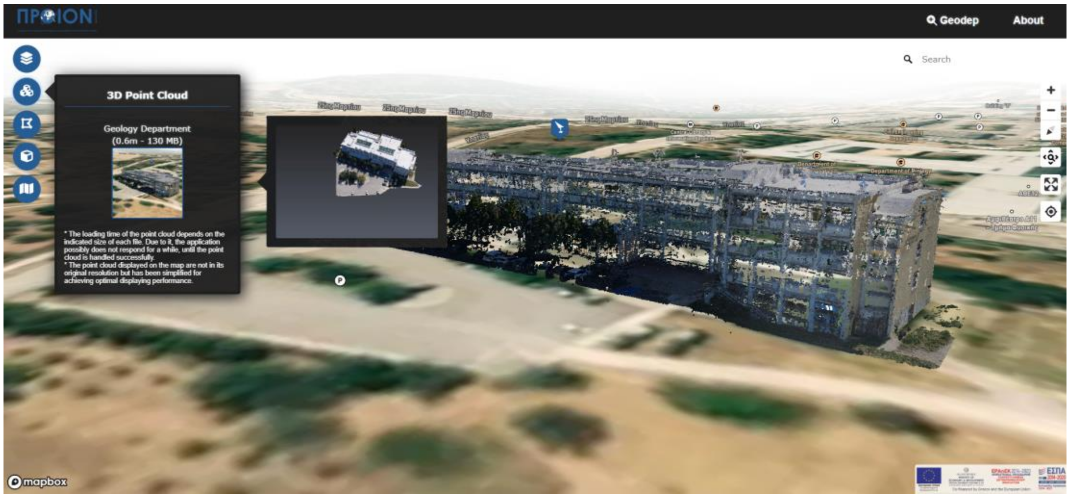

Figure 9. The point cloud of the monitoring building of the Geology Department is rendered on the 3D map environment.

6. FUTURE INSIGHTS

The PROION project introduces a novel multiparametric framework for the holistic monitoring of critical infrastructures, combining a wide dataset of different spatiotemporal observations and measurements. The GNSS and InSAR land movements, in combination with their future spatial prediction resulting from the fuzzy logic networks (FLN) methods and the followed validation techniques based on high-resolution 3D point clouds, as well as several supportive measurements and data, such as earthquakes and micro-accelerometer events, meteorological information and the geological map of the monitoring area, compose a high performance and enhanced framework, for efficient near real-time monitoring, based on EO and in-situ data.

The PROION's Web GIS platform is developed as a modern web-based solution for encompassing, accessing, analyzing, and visualizing the data outcomes of the project, providing useful advanced spatial tools tailored to the needs of precise and multiparametric spatiotemporal analysis. Leveraging state-of-the-art technological solutions for data handling and visualization, as well as for the development of a user-friendly interactive component-based web platform, the Web GIS platform is developed and parameterized to provide an advanced end-user experience through an interactive 3D virtual Earth environment and dynamic interactive charts.

Establishing an automatic seamless data generation and storage procedure, PROION's Web GIS platform does not constitute a solution dedicated only to the project's life cycle. On the contrary, the methodological framework and the Web GIS platform are developed focusing on the future exploitation of the produced knowledge, data and platform. Following the guidelines of an agile architecture both in the back-end and front-end development, the platform is adaptable to different and greater monitoring scenarios which require wider and denser networks of GNSS stations and Radar Corner Reflectors. Additionally, the spatiotemporal filters have been developed to offer the capability to manage efficiently big time series data with wide spatial extent, following the logic of a multidevices operational scenario.

The introduced version of the Web GIS achieves a high Technology Readiness Level (TRL) near eight, considering its successful operation of it in three real-life case study scenarios; a building located on the Patras University campus, a dam, and an active landslide within the Enceladus Hellenic Supersite area. The successful development and commercialization of PROION's Web GIS platform, as a ready service for full commercial deployment that ensures seamless and smooth operation, are strongly dependent, not only on end-users' feedback but also, on future testing on different monitoring scenario scales, leading to the generation of significant useful information for the further refinement and adjustment, aiming to reduce the risk of operational errors.

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