An open source WebGIS approach to empower glacier research with scalability and reproducibility

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Abstract

Glacier monitoring is a key component in understanding climate change, especially for small and rapidly retreating glaciers in regions like the Alps. These ice bodies, though limited in size, play a crucial role in local water resources, ecosystem stability, and natural hazard management. However, their fragmented terrain poses significant challenges for data collection and interpretation. This study presents a WebGIS platform developed for the Belvedere Glacier (Italian Alps), designed to enhance data accessibility, visualization, and analysis through a low-cost, open-source solution. The platform integrates heterogeneous datasets — including GNSS measurements, displacement, velocities and acceleration time series — using CesiumJS for 3D geospatial visualization and PostgreSQL/PostGIS for spatial data management. It allows users to explore monitoring points, visualize glacier dynamics, and perform comparative temporal analyses via an intuitive interface. Built entirely with Free and Open Source Software for Geospatial, the system supports both data upload and export, promoting collaborative workflows and reproducibility. Designed with usability in mind, the platform targets a broad audience, from researchers to policymakers, and demonstrates the potential of WebGIS to support long-term glacier monitoring. The proposed architecture is transferable to other environmental applications, contributing to the digital transition in climate impact documentation.

1. Introduction

Glacier monitoring activities are essential practices for understanding climate change. This is especially true for smaller glaciers, which are highly influenced by global warming and face the most rapid mass losses, impacting also economical sustainability of the local community. In recent studies, the Glacier Mass Balance Intercomparison Exercise team (GlaaMBIE, 2025) provided a global assessment of glacier mass changes from 2000 to 2023. Observations from the last two decades of monitoring glaciers at a global scale revealed an alarming acceleration in mass loss, particularly in regions with small glacier areas. In particular, Central Europe, including the Alps, experienced the most dramatic relative loss (-39%), highlighting the vulnerability of mid-latitude glaciers. Despite their relatively small size compared to glaciers from the polar and Himalayan areas, these ice bodies play a crucial role in regional water resources and ecosystem stability (Nesur et al., 2022). Hugonnet et al. (2021) provided further evidence of this acceleration, reporting a global glacier mass loss rate of 267 gigatonnes per year between 2000 and 2019, which exceeds the combined ice loss of Greenland and Antarctica. Smaller glaciers, such as those in the Alps, are particularly challenging to monitor due to their fragmented nature and steep, complex terrain, which often limits data coverage and increases uncertainty in documentation (Triglav Čekada et al., 2020, Prinz et al., 2018). High-resolution Digital Elevation Models (DEMs), such as those provided by the Pléiades Glacier Observatory, provide timing insight into these changes (Berthier et al., 2024). Given their importance for water supply and natural hazard management, the capacity to maintain long-term, high-precision monitoring and data management systems is crucial to reduce observational uncertainties and inform adaptation strategies (Gärtner-Roer et al., 2019).
In this context, Web Geographic Information System (WebGIS) platforms, by integrating heterogeneous geospatial datasets, can provide interactive assessments of environmental conditions, support change detection, and enhance decision-making (Vinueza-Martinez et al., 2024), representing a first step towards the adoption of fully functional digital twin solutions (Fissore et al., 2023).
Moreover, WebGIS combined with advances in cloud computing, adoption of open-source software, and integration of mobile technologies further improve their efficiency for development of re-adaptable and reproducible solutions (Kipkemboi et al., 2023). This flexibility, coupled with the ability to manage large datasets and communicate insights through user-friendly visualizations, has promoted their widespread adoption in different domains of environmental monitoring (Toro Herrera et al., 2021). For instance, in water resource management, a WebGIS environment can facilitate real-time monitoring of parameters such as chlorophyll-a concentration, suspended matter, and surface water temperature, aiding awareness and policymaking (Biraghi et al., 2022).
Similarly, in glacier monitoring, capacity-building initiatives are emerging, ranging from the first attempts to build a unified regional inventory for glacier conditions (Smiraglia et al., 2015) to the integration og remote sensing products and open data from field surveys into centralized WebGIS platforms (Senger et al., 2021). These systems address challenges posed by harsh environments and accessibility issues, enabling data sharing and visualization to improve research and fieldwork efficiency. However, usability and ease of access for different non-specialised end users still represent challenges to be properly addressed in platform design phases (Gaspari et al., 2025).
This work presents a WebGIS platform designed to facilitate the exploration and analysis of the monitoring data of the Belvedere Glacier in the Italian Alps. By integrating geospatial visualization and interactive data analysis, the platform offers an intuitive environment for researchers, environmental agencies, and stakeholders, leveraging low cost Free and Open Source Software for Geospatial (FOSS4G).

2. Platform design and implementation

The WebGIS platform presented in this study has been designed to offer an integrated and open-source solution for the analysis and visualisation of environmental monitoring data, with particular attention to glacier-related datasets. The entire architecture is built upon open standards and well-established geospatial technologies to ensure reproducibility, flexibility, and long-term maintainability. By adhering to the FOSS4G principles, the platform ensures transparency, cost-effectiveness, and adaptability, which are critical in long-term environmental monitoring contexts. The approach focuses on three key components: identification of target users and needs, platform architecture design, backend and frontend development and implementation. These components are interlinked to allow efficient spatial queries, time-based data exploration, and field data integration.

2.1 Identification of target users and needs

The platform was conceived as a dynamic tool to support exploration and analysis of data, intended to serve a broad audience with varying needs. The key user groups identified during the design of the platform are:

- local communities who are directly impacted by glacier-related hazards; their primary need is timely and accessible information with a user-friendly interface for easy navigation and understanding;
- researchers who require access to real-world, and up-to-date geodata for educational purposes, multidisciplinary collaborative projects, and advanced scientific analysis; the platform serves as a repository for data derived from multiple monitoring campaigns, supporting coursework, lectures, labs, and studies on glacial dynamics and climate change impacts.

2.2 Software architecture design

The platform architecture is composed of three layers: a PostgreSQL/PostGIS spatial database, a Django-based backend, and a CesiumJS-powered frontend. The roles of each layer and their interactions are illustrated in the schema in Figure 1.

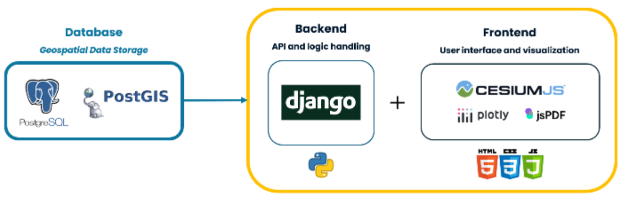

Figure 1. Software architecture designed for the WebGIS prototype focused on glacier monitoring. Each layer is built on top of FOSS4G.

PostgreSQL 17 ensures robustness and scalability, while the PostGIS 3.5.2 extension enables efficient storage and querying of spatial data (McKenna & PostGIS Team, 2021). Built on previous work by Bonora (2023), the data model has been structured to include multiple types of monitoring data, in particular point-based GNSS measurements, data on 2D and 3D products such as orthophotos, UAV-derived products, and historical imagery obtained as output of documented in-situ surveys.
The backend was developed using Django, a high-level Python web framework (Sharma et al., 2024). It is the component that connects the user interface to the database and manages data-processing tasks.
On the frontend, CesiumJS, a JavaScript library, was selected for the interactive geospatial viewer. It allows high-performance rendering of terrain models, vector layers, and imagery, and it supports camera controls and time-dynamic data (Liu et al., 2023).
The integration between Django and Cesium is achieved through JavaScript Object Notation (JSON)-based endpoints and HTML templates, making it possible to load georeferenced entities such as points, lines, and raster data directly into the browser. To implement the platform, different programming languages were used for different parts of the system. Python was used for the backend logic, while JavaScript was used on the frontend. HTML and CSS were used to build the structure and style of the web pages.

2.3 Platform implementation

The platform was developed using Django, which follows the Model-View-Template (MVT) architecture. Models define how data is stored, views handle the logic, and templates control what the users see in the browser. The database schema includes time-stamped records per point ID, supporting temporal queries and visualizations. Validation routines check for temporal consistency, coordinate range errors, and duplication during upload.
The project was set up with a clear structure, using separate folders for models, views, templates, static files, and settings. The database tables were connected to Django using GIS-enabled models. URL patterns were added to link each view to the right page, such as the *home*, *login*, and *upload_data* pages, respectively responsible for the main map view visualisation, the user roles access and management and the new data uploading.
The *home* view reads the data from the database, transforms the coordinates, and sends the results to the frontend in JSON format. CesiumJS shows the map with the measurement points, Plotly is used to display time-series graphs and jsPDF is used to let users export the survey data to PDF.
A *login* page system was added to limit the upload function to authorized users. The *upload* page accepts Comma Separated Values (CSV) files, checks if the data is complete, and saves new measurements into the database.
The source code of the developed platform is available on GitHub (https://github.com/labmgf-polimi/belvedere-webgis), thus enabling a collaborative approach to feedback-driven enhancement of subsequent versions of the WebGIS prototype.

3. Case study

The system was tested and applied to a real-world case: the monitoring of the Belvedere Glacier, located in the Anzasca Valley (Piemonte, Italian Alps), on the eastern side of Monte Rosa (Figure 2). It is the terminal part of a larger glacial valley that includes Nordend Peak (4612 m) and Dufour Peak (4633 m). It's a temperate glacier characterized by a debris-covered surface. It extends from about 1800 m to 2250 m in altitude, has an area of 1.8 km² and a length of about 3000 meters with a maximum width of 500 meters.
The glacier can be divided into three sectors: the upper part where snow and debris accumulate, the central transfer zone with high ice flow, and the lower part where it splits into two tongues. In recent years, their different dynamics led to the adoption of different approaches to document in-situ surveys. In the early 2000s, the site experienced a surge event with velocities up to 200 m/year, followed by a phase of retreat that continues today (Ioli et al., 2022). The glacier has also caused natural hazards

such as floods and slope instabilities, especially near the village of Macugnaga.

Since 2015, the Belvedere Glacier has been monitored annually by the Department of Civil and Environmental Engineering of Politecnico di Milano. Monitoring is based on two main methods: GNSS measurements and UAV photogrammetry. GNSS is used to measure fixed and moving points placed on the glacier surface. For each point, the position is recorded in terms of east, north, and elevation, and these values are compared over time to calculate displacement, velocity, and vertical changes. The UAV campaigns produce high-resolution orthophotos and DSMs, which are used to analyse surface morphology and volume variations. Since 2018, the activities have been included in the Summer School (Gaspari et al., 2024) organized by the Geodesy and Geomatics Section of DICA at Politecnico di Milano, where students engage in fieldwork and gain practical experience.

In addition to this data, historical aerial images from 1977, 1991, and 2001 were used to reconstruct the glacier past morphology. Moreover, two time-lapse cameras were installed on the glacier to capture continuous visual data, useful for identifying sudden events like collapses.

The developed WebGIS platform is built on top of the collected knowledge of the glacier, integrating into the existing Belvedere Glacier monitoring ecosystem, which already includes a structured spatial database (Bonora, 2023) and the GlacioTools QGIS plugin (Fajardo Turner, 2024; Fajardo Turner et al., 2025) developed through the adoption of open-source tools.

Figure 2. View of the north-western lobe of the Belvedere Glacier. This section is characterised by the presence of debris collapses and landslides, which are particularly prevalent in the downstream valley of the Macugnaga municipality.

4. Results

This section presents the structure and features of the developed WebGIS platform, focusing on how the system supports the visualization and analysis of glacier monitoring data. The functionalities of the WebGIS platform were tested with the Belvedere Glacier data, exploring spatial and temporal patterns of surface displacement, velocities and accelerations. The results are discussed in terms of interface design, available tools, data interpretation capabilities.

The application opens with the home page displaying an interactive map, where users can explore the glacier area by zooming, rotating, and panning the view. This page also contains a legend, a filtering panel and an export/import button section (Figure 3). Monitoring points are shown by default on the surface of the glacier and differentiated by colour.

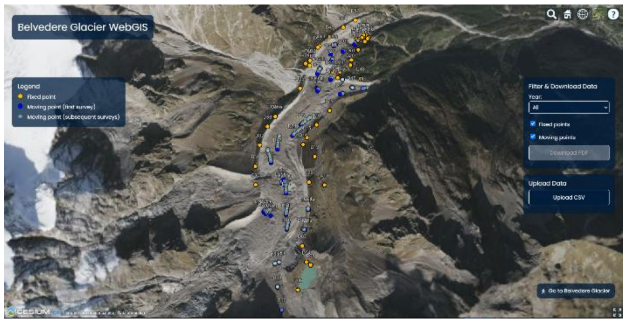

Figure 3. Home page of the WebGIS with the Cesium-based visualisation.

The legend shows that fixed points are in yellow while moving points are displayed in blue tones, with darker blue for older surveys and lighter blue for more recent years, providing an intuitive distinction of points dynamics and acquisition timeline. The filtering panel on the right hand side allows users to select specific campaigns or point type. It is possible to select a specific survey year from a dropdown menu and choose whether to view fixed, moving, or all points, querying the database in an interactive way.

When a user clicks on a moving point, a chart appears showing the time-series evolution of different parameters: east, north, elevation (h), displacement, velocity, and acceleration. The displayed parameter can be changed using a dropdown menu (Figure 4 and 5). The data is visualized using Plotly, which allows interactive features such as zoom into specific time intervals, hover over points to read exact values, and export the plots as images.

In the lower right corner of the screen, a "*Go to Belvedere Glacier*" button allows users to reset the map view to the glacier area. In the top right corner, a set of buttons enables changing the basemap for better contrast or searching for a specific location. For example, based on project needs, custom Web Map Services of orthophotos or geological or hazard thematic mapping can be inserted, allowing users to overlay additional information with the measured points.

The CesiumJS-based viewer also facilitates the exploration of the third-dimensional component of the dataset of yearly measured Ground Control Points along the glacier. Moreover, this choice ensures compatibility with the most recent Open Geospatial Consortium (OGC) standards for data sharing on web environments, in particular 3D tiles. In this way, tiled point clouds and models can be easily deployed on the application, furtherly enhancing integration of a wide range of data formats.

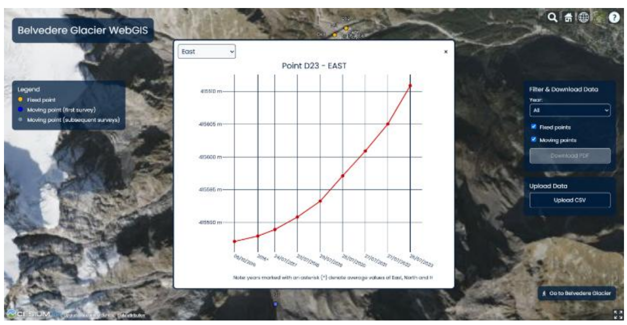

Figure 4. Graph visualisation of East coordinates measurements timeline for a selected point on the glacier.

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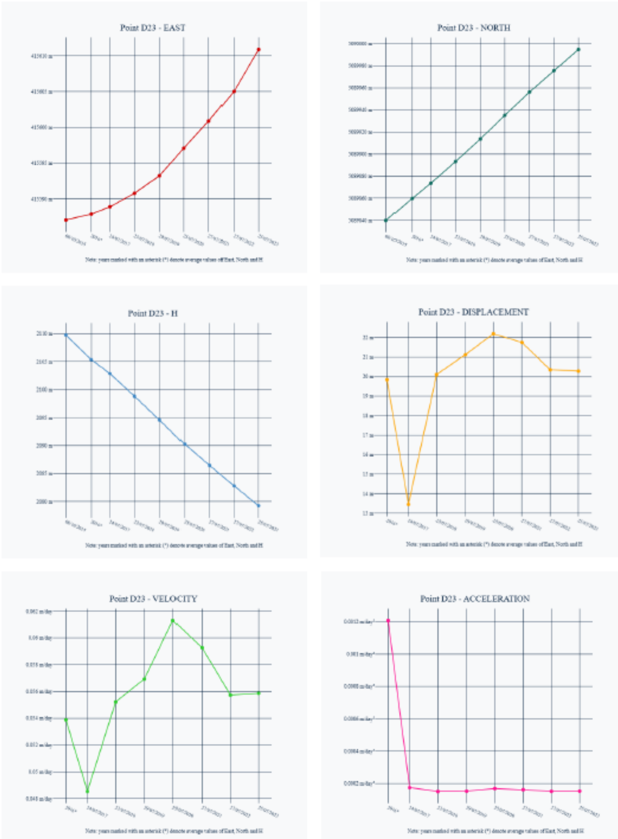

Figure 5. Example of the different graphs dynamically created in the platform when choosing a parameter of interest for a monitoring point. The adoption of Plotly supports the export in image format as well as the interactive zooming and rescaling of the graph.

The platform also supports uploading new measurement data. Indeed, through a dedicated login page, authorized users can authenticate and access the data upload interface. The system accepts Comma Separated Values files containing GNSS survey data. Required fields include point label, measurement date, east, north, h, latitude, and longitude (Figure 6). Upon submission, the system checks the format of the file and verifies that the necessary columns are included. If the validation is successful, the data is automatically inserted into the PostgreSQL database and becomes immediately available in the WebGIS interface. This sequence of operations simplifies the periodical update of the database with the newly collected field data, automatising in a single place insertion of new documentary records on multiple joined tables. This process ensures consistency on primary keys while avoiding loss of interconnection between tables in relationships due to manual insertion errors.
A PDF export functionality is available for each survey. After selecting a year, users can download a report containing a snapshot of the map and a table with all point measurements for that year. This function uses jsPDF and is particularly useful for generating quick overviews and reports for documentation and planning of future field operation as well as for external communication (Figure 7).

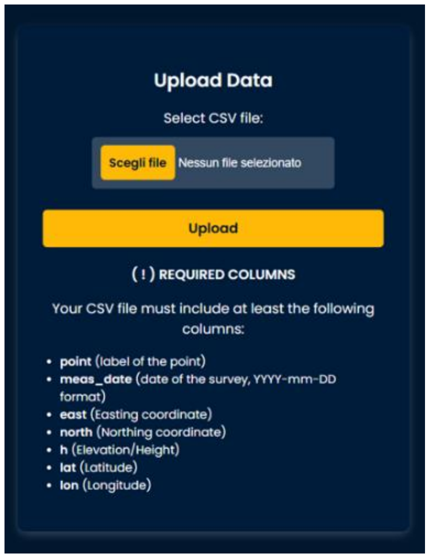

Figure 6. After login, authorized users can authenticate and access the data upload interface.

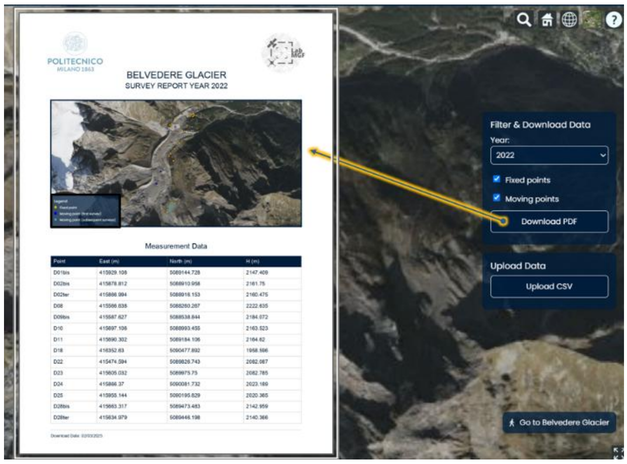

Figure 7. Example of automatic generation of a report for the survey of 2022. This function puts together in a simple view quantitative information useful for future planning.

5. Discussion

The Belvedere WebGIS platform enables to display patterns of glacier surface motion through interactive charts and point trajectories. By visualizing the positions of monitoring points across multiple years, users can easily observe how different areas of the glacier behave over time.
The central part of the glacier, where ice thickness is greater and friction with the valley walls is lower, shows more significant and consistent displacement. In contrast, the lateral, upper and tongues sectors experience slower and more irregular motion, influenced by topographic constraints and variable ice deformation. These differences are immediately visible in the map view and are confirmed by the length and direction of motion trails, as well as by the evolution of velocity and acceleration in the time-series graphs.
The platform simplifies the generation and exploration of these visualizations, removing the need for external tools or complex workflows. Similar analyses can be carried out in QGIS, but they often require manual steps such as filtering layers or creating layouts. The WebGIS automates these processes, saving time and reducing the risk of manual errors.

In this respect, the platform complements glacier-specific existing tools like the GlacioTools QGIS plugin. The plugin offers advanced and customizable analyses for expert users, while the WebGIS focuses on simplicity and accessibility through a cloud-based environment, providing fast and intuitive access to glacier monitoring data to a wider audience.

Because of its structure and intuitive tools, the WebGIS can be used by a wide range of users. Glaciologists and researchers can perform temporal and spatial analyses directly from the interface, selecting specific points and interpreting trends. Field technicians, that can already take advantage of the seamless integration of Qfield and MerginMaps with the PostgreSQL database, can also review past measurements and upload new ones without needing external tools. The upload function validates the CSV structure, avoiding the proliferation of duplicates, some types of inconsistencies and the risk of data loss in fragmented external spreadsheet files.

The platform can also serve educational and communication purposes. Students can explore the glacier evolution through time-series charts and visual maps, improving their understanding of glaciological processes. Public authorities and local stakeholders, such as those from the nearby town of Macugnaga, can use the WebGIS to observe the state of the glacier and be informed on future community-participated risk prevention strategies. The simple structure of the interface, that include dropdowns, charts, filters, and exports, makes the platform accessible even for users with no GIS experience.

Finally, although the platform was developed for the Belvedere Glacier, the system is scalable and adaptable, taking advantage of low-cost and low-code solutions. The database structure and platform logic can be extended to other glaciers or environmental monitoring contexts. The use of GNSS data, survey IDs, and point associations is generalizable, so the same workflow could be applied to study glacier motion elsewhere. Moreover, the export and upload functionalities support continuous data integration, allowing the platform to grow and evolve over time in compliance with new standards. According to user needs, the platform architecture can also be extended to support comparative analyses between locally acquired field data and global Digital Terrain Models (DTMs), such as Shuttle Radar Topography Mission (SRTM), Copernicus DEM or NASADEM, by integrating data access and request through the OpenTopography API (Krishnan et al., 2011). This would enhance the platform's utility in multi-scale assessments, providing context for local changes within broader geomorphological trends.

6. Conclusions and future developments

The development of the WebGIS platform dedicated to the monitoring of the Belvedere Glacier represents a pilot study for the reproducible digitalization, accessibility, and interactive analysis of glaciological datasets. Designed as an open-source, web-based solution, the platform serves as a multi-disciplinary tool for researchers, environmental agencies, and local decision-makers, enabling the spatial and temporal exploration of glacier dynamics with an intuitive, customisable and accessible approach.

Built upon CesiumJS for geospatial visualization and Django for logic handling, the platform offers functionalities such as interactive navigation through the glacier surface and monitoring points, visualization of displacement trends over time, comparison of multi-temporal measurements, and graph-based analysis of point movements. It also supports data upload and export capabilities, promoting collaborative workflows and further analysis.

Despite its potentials, several challenges remain and need to be addressed in the future works. The platform effectiveness is closely tied to the quality, consistency, and resolution of input data, which depend on the accuracy of the original survey methods, requiring additional standardization processes.

To further strengthen its role as a monitoring and decision-support tool, several enhancements are planned. They include integrating orthophotos and high-resolution 3D products for more realistic terrain representation and improving temporal visualization through animated 3D time-series that display point displacements as dynamic trajectories. For this purpose, analysis of independent 3D datasets using Cesium's 3D Tiles, along with improved management of raster data via GeoServer and WMS integration are under evaluation. A key goal is to incorporate real-time data streams from in-situ sensors (e.g., weather stations) to enable near real-time monitoring and coupling of different physical parameters.

Deployment on an openly accessible server is currently in progress and a public instance will be deployed following internal testing and optimization by the end of the year. Future improvements will target interface design, visualisation techniques and performance optimisation to support increasingly large and complex datasets. These developments will make the platform a comprehensive, intelligent system that advances research, supports decision-making and strengthens digital responses to climate-driven glacier change.

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