GlacioTools: Streamlining Glacier Feature Monitoring and Reporting in QGIS

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Abstract

Mountain glaciers are highly sensitive to climate change, having lost nearly half their surface area and two-thirds of their volume in the European Alps since 1850. Recent advances in unmanned aerial vehicles (UAVs) and aerial imagery, combined with traditional in-situ Ground Control Points (GCPs) measurements, have enabled repeated data collection for glacier monitoring. However, analyzing and visualizing glacier changes remains a time-consuming process in Geographic Information System (GIS) environments.
QGIS, an open-source GIS, supports custom plugins that automate routine tasks, improving accessibility and collaboration in climate research. Existing plugins facilitate environmental monitoring, hydrology, and remote sensing applications, streamlining spatial analysis without requiring programming expertise. Despite these tools, an integrated, user-friendly solution for glacier monitoring is still lacking. In this paper the GlacioTools QGIS plugin is presented. It is designed to simplify geospatial data processing for glacier studies. It automates in-situ survey reporting, generates surface displacement and velocity maps, and organizes GCP documentation within a single workflow. By enhancing efficiency and accessibility, GlacioTools supports researchers in documenting and analyzing glacier evolution more effectively.

1. Introduction

Mountain ecosystems, particularly the alpine cryosphere, are extremely sensitive to climate change, with glaciers experiencing significant reductions in area and volume. Indeed, between 1850 and 2000, glaciers in the European Alps lost half of their surface area and about two-thirds of their volume (Taylor et al., 2023). In the last two decades, the rapid technological development and cost reduction in the field of unmanned aerial vehicles (UAVs) and the increasing availability of aerial imagery (Ioli et al., 2021), combined with traditional in-situ Ground Control Points (GCPs) measurements, have allowed the implementation of repeated data collection campaigns to document glacier evolution through orthophotos and digital surface models (DSMs) (Di Rita et al., 2020). However, routine operations to gain insights and visualise results on volume loss, surface dynamics often require manual execution of step-by-step time-consuming operations in Geographic Information System (GIS) environments. Due to its open-source nature, QGIS not only offers the possibility to develop customisable plugins that facilitate the execution of routine operations (Coetzee et al., 2020) but also promotes collaboration and increases accessibility in multidisciplinary research teams for the adoption of effective solutions for climate change research. QGIS plugins have been developed to address a wide range of challenges and provide specialized tools across various domains (Duarte & Teodoro, 2021). In the field of environmental monitoring and management, they support the analysis of landscape changes (Wright et al. 2024), soil degradation, and natural hazards (Albano et al., 2017), facilitating the identification of spatial patterns over time. Additionally, QGIS plugins streamline spatial modelling tasks, by allowing users to conduct all necessary steps within the same GIS environment without requiring advanced programming skills. They also play a crucial role in hydrological (Renard et al., 2024) and agricultural studies (Dhonthi et al. 2024), meteorology (Touati et al. 2020), and remote sensing, enhancing data accessibility and interpretation for applications such as groundwater vulnerability assessment (Duarte et al. 2019), land use analysis, and satellite imagery processing (Marzouki et al., 2025). These functionalities highlight the adaptability of QGIS as a key resource for geospatial research and decision-making in climate-related studies. However, despite the evidence of the emergence of climate change, literature lacks proper user-friendly integrated toolkits for analysing and documenting activities of glacier monitoring.
This work presents the design and implementation of GlacioTools, a plugin which aims to facilitate accessibility to geospatial data and execution of routine analysis operations in a single space when monitoring glacier sites. It also aims to provide easy-to-use tools for improving the reporting of in-situ surveys, automating the generation of surface displacement and velocity maps, and monographs of GCPs that are repeatedly measured on field.

2. Tool design and implementation

The workflow adopted for the development of GlacioTools consisted of three key steps: (1) analysis of end-user requirements, (2) design of functional components, and (3) implementation of the plugin code. These steps ensured that the tool effectively met the needs of glacier monitoring professionals by providing an automated and standardized solution within the QGIS environment.

2.1 End-User Requirement Analysis

The initial step involved understanding the primary requirements of end-users, particularly researchers and professionals involved in monitoring campaigns. As a reference the Belvedere Glacier Monitoring Program by Politecnico di Milano was used (Gaspari et al., 2025). The monitoring program involves yearly survey campaigns on the Belvedere Glacier by researchers, faculty, and students. Traditional glacier monitoring methods generate a variety of geospatial datasets that require structured processing and interpretation. The most common data formats include:

- Digital Surface Models (DSMs): Yearly raster datasets derived from photogrammetry or LiDAR surveys, representing glacier surface elevation. These models are used to track elevation changes and volume loss over time.
- Ground Control Points (GCPs): Georeferenced point vector data, typically collected through Global

Navigation Satellite System (GNSS) surveys. These serve as reference points for geospatial analysis and are crucial for measuring glacier displacement, velocity, and acceleration when compared across different time intervals. An example can be seen in Figure 1.

- Orthophotos: High-resolution, geometrically corrected aerial images that serve as a visual reference for manual feature extraction, particularly when identifying homologous points on glacier surfaces for interpolation.

Figure 1. Image of a GCP located on the Belvedere Glacier measured with a GNSS antenna.

After each yearly campaign, the team must process the collected data to transform it into more insightful formats for the analysis and diagnosis of the glacier. The key data processing outcomes discussed with the monitoring team included variations in glacier elevation, which allow to identify regions experiencing ice loss or accumulation, to detect low-lying areas prone to meltwater pooling, and to estimate the glacier volume change over time. Additionally, glacier displacement and velocity measurements provide insights into the glacier response to environmental changes, help predict instabilities, and aid in planning mitigation strategies for potential surges or collapses. Lastly, GCP monograph reporting simplifies the registration and updating of Ground Control Points, streamlining the workflow for future yearly campaigns.

As of the time of the development of the plugin in 2024, no single tool or plugin was found with the capacity to quickly and easily process periodical glacier monitoring data into the required final formats.

2.2 Design of functional components

Given these data requirements, GlacioTools was structured into three functional modules, each addressing a key analytical task required in glacier monitoring.

The first module, Variations Calculation, is responsible for computing elevation and volume differences between Digital Surface Models. It allows the user to apply a glacier boundary mask and then proceeds calculating height and volume changes. Since DSMs have typical resolutions in the range of pixel metrics, this module ensures high spatial accuracy in detecting surface changes. Additionally, it provides descriptive statistics summarizing the changes, such as mean and total changes, and standard deviation. These outputs enable a robust quantitative analysis of glacier dynamics.

The second module, Interpolation, processes periodic GCPs coordinate measurements, as well as homologous points manually picked from orthophotos. It allows users to apply geospatial interpolation techniques to generate continuous surface maps of glacier displacement, velocity, and acceleration fields. Currently, the user may select between Inverse Distance Weighting (IDW) and Triangulated Irregular Network (TIN) as interpolation methods. The results are automatically transformed into a QGIS map layout, allowing users to visualize glacier surface motion trends over time.

The third module, GCP Reporting and Monograph Generation, streamlines the production of standardized GCP reports. These reports may include the coordinates from up to three previous surveys, and facilitate the data input for description, location, route to get to the GCP, and photos of the location. The monographs generated through this module serve as valuable resources for scientific reporting, long-term comparative studies, and archival purposes.

Module	Input	Processing	Output
Variations Calculation	Two DSMs in raster format	Raster calculation with additional user input	One raster file with variations
Interpolation	Vector data points with a numerical field to be interpolated (GCPs and/or homologous points)	Geospatial Interpolation methods as IDW and TIN	One raster file with interpolated values
Monograph	Vector Data point (GCPs), prompted text, and images	Coordinate extraction and standardized layout arrangement	Editable QGIS layout that can be exported as image or PDF

Table 1. Description of data input, output and processing for each module of the GlacioTools plugin.

By automating these three core processes, GlacioTools significantly reduces the time required for glacier monitoring while ensuring reproducibility and standardization of results.

2.3 Implementation of the plugin code

Once the required functionalities were defined, pseudocode structures were developed to outline the sequence of processing steps for each module. These pseudocode designs allowed for logical validation of the workflow before implementation, ensuring that all necessary input parameters, computations, and outputs were properly accounted for.

The implementation phase was carried out using PyQGIS, the Python API for QGIS. This programming environment was chosen due to its direct integration with QGIS functionalities, enabling efficient geospatial processing within an open-source framework.

The core development process of GlacioTools followed a structured sequence of steps to ensure its functionality and seamless integration with QGIS. The first step involved setting up the plugin framework. The basic file structure was easily created with the Plugin Builder, an open source QGIS plugin. The Essential Python scripts were developed to define the backend processing logic for Raster Calculations, Vector Point

Interpolations, and automated reporting, forming the foundation for the analytical capabilities of the tool.
Next, the development of the graphical user interface (GUI) was carried out using Qt Designer, a drag-and-drop GUI builder integrated with QGIS. The interface was structured into separate tabs corresponding to each functional module, making it easy for users to navigate through different processing options. An example of this GUI can be seen in Figure 2.

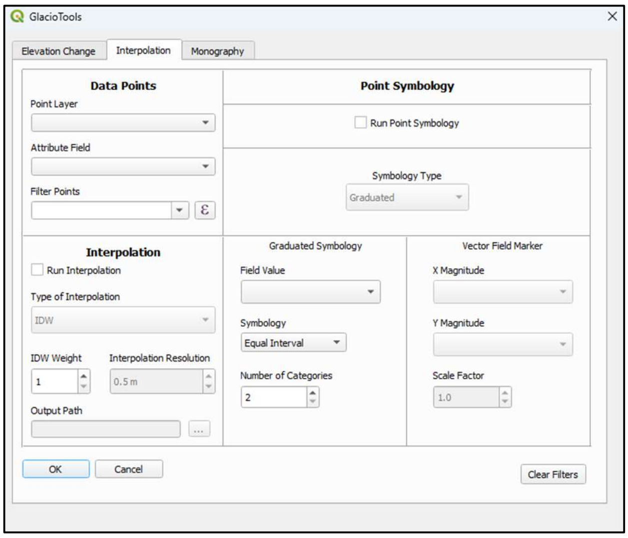


Figure 2. Example of the GlacioTools plugin GUI in the QGIS environment. The screenshot shows the Interpolation tab with the requested parameters to be defined through user input.

Following this, the integration with the QGIS Processing Framework ensured that the plugin could leverage QGIS native raster and vector processing algorithms for elevation change analysis, interpolation, and symbology application. The plugin automatically styled and visualized output layers, allowing users to immediately interpret the results without additional processing.
To validate the accuracy and reliability of the tool, testing and debugging were conducted using historical data from the Belvedere Glacier monitoring project. A series of test cases were executed to verify that each module produced the expected results. Throughout development, the Plugin Reloader tool was extensively used to facilitate quick debugging within the QGIS environment.
The final version was released as an open-source plugin hosted on GitHub at https://github.com/sfajardot/GlacioTools. The repository includes full documentation, installation instructions, and a sample dataset, enabling users to easily install and test the plugin functionalities. The open-source deployment of GlacioTools ensures accessibility and community collaboration.

3. Results and discussion

The core functionalities of GlacioTools were systematically tested using Digital Surface Models (DSMs) and Ground Control Points (GCPs) from the Belvedere Glacier monitoring project (Ioli et al., 2024). This long-term initiative, conducted in the Italian Alps by the Department of Civil and Environmental Engineering at Politecnico di Milano, has consistently collected high-resolution photogrammetric data and GNSS measurements to track the glacier evolution.
The evaluation of the plugin was based on its three primary functionalities: analyzing elevation and volume changes through DSM differencing, computing surface displacement, velocity, and acceleration using GCP interpolation, and generating automated reports of GCP time series for documentation and field planning. GCP coordinate measurements were accessed internally via a PostgreSQL database connection, ensuring seamless data retrieval for automated analysis. However, these datasets are also publicly available on the project dedicated website (thebelvedereglacier.it), allowing broader accessibility for researchers and practitioners.

3.1 The Belvedere Glacier

The Belvedere Glacier, located on the east face of the Monte Rosa, in the Anzasca Valley, Italy, constitutes the terminus of the glaciers descending the steep eastern slope of Monte Rosa in the Italian Alps (Diolaiuti et al., 2003) (Figure 3). It is a temperate alpine glacier, which extends from a maximum altitude of around 2250 meters above sea level down to 1800 meters a.s.l., where it splits into two distinct glacier tongues. It covers an area of approximately 1.8 square kilometers, and it is mainly elongated in the South-North direction, with a length of nearly 3 kilometers and a maximum width of 500 meters (Ioli et al., 2022).

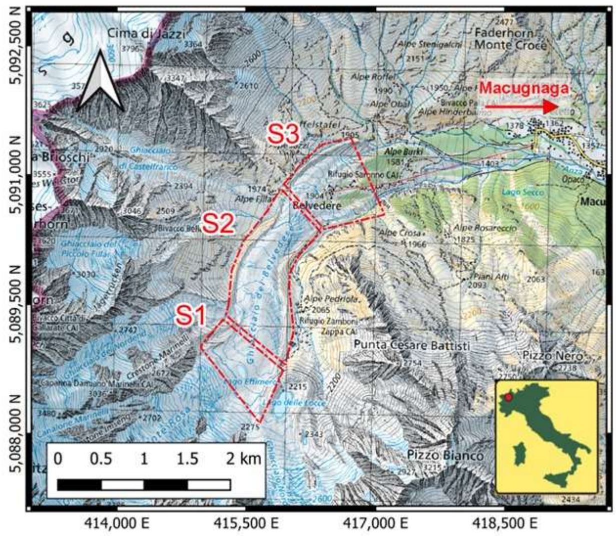


Figure 3. Map of the Belvedere Glacier, with its morphological sectors: S1 represents the accumulation zone, S2 corresponds to the transfer zone, and S3 is the low-relief zone containing the two glacier tongues (Ioli et al., 2021). Coordinates are referenced in ETRF2000(2008)—UTM 32N. [Basemap source: Swisstopo]

The Belvedere is a typical debris-covered glacier (Figure 4), similar to the Miage glacier (Monte Bianco, Valle d'Aosta). Furthermore, the glacier has a small accumulation basin, fed almost entirely by avalanches originating from the eastern slope of the Monte Rosa, which is more than 4500 m a.s.l. (Diolaiuti et al., 2003). It is particularly relevant to note that until the first years of this century, the Belvedere was one of the few glaciers in the Alps that did not retreat, thanks in part to the cover provided by rocks and debris. In fact, during the period 2000-2001, the Belvedere experienced an enormous surge, when a sudden increase in ice mass at the base of Monte Rosa flowed towards the valley in the form of a kinematic wave (Haberli et al., 2002). However, in recent years the debris protection has not been enough to limit the glacier retreat and loss of volume. Between 2001 and 2009, the Belvedere lost an average of 5.97 million cubic meters. In the next decade from 2009 to 2019 the trend continued to be negative, but less severe, with an average loss of 2.72 million cubic meters per year (De Gaetani et al., 2021).

Figure 4. View of the north-west tongue of the Belvedere debris-covered glacier (morphological sector S3).

3.2 Elevation and Volume Change Analysis

The Variations Calculation tab of the plugin was applied to the glacier DSMs spanning from 1977 to 2023. An example of the plugin in the QGIS interface can be seen in Figure 5.

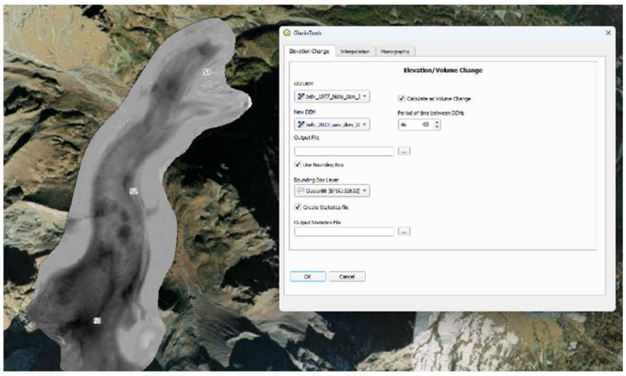


Figure 5. Example of the QGIS interface for the Elevation and Volume Change analysis within the GlacioTools plugin.

The plugin automatically computed the elevation differences between consecutive DSMs, applied a glacier boundary mask, and generated descriptive statistics summarizing the changes in ice surface elevation and total volume. The analysis showed a total ice volume loss of approximately 81 million cubic meters over the entire 46-year period (1977–2023). Notably, a substantial 22 million cubic meters were lost between 2015 and 2023 alone, highlighting the intensified glacier retreat in recent years. An example of a map resulting from this analysis is presented in Figure 6.

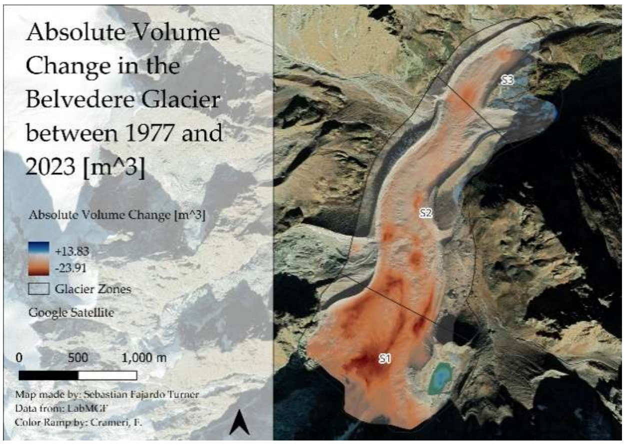


Figure 6. Example of map with volume change in the Belvedere Glacier 1977-2023.

The analysis also revealed that the highest rates of ice loss occurred during the periods 2001–2009 and 2015–2023, both of which coincided with strong climatic warming trends. However, some localized positive elevation changes were detected for specific epochs, likely resulting from transient ice accumulation zones or potential errors in DSM co-registration, necessitating further validation. Additionally, the spatial distribution of elevation change was influenced by the debris-covered glacier surface, with lower ablation rates observed in debris-insulated areas, a phenomenon frequently documented in similar alpine glacier environments.

3.3 Glacier Surface Displacement, Velocity, and Acceleration Analysis

The Interpolation tab of the plugin was used to generate spatially continuous maps of glacier displacement, surface velocity, and acceleration fields. The input data for this process included periodic GCP coordinate measurements obtained through GNSS surveys, providing precise geospatial reference points. Additionally, manually selected homologous points on orthophotos were incorporated to enhance interpolation accuracy, ensuring a more reliable representation of glacier motion patterns.
A detailed analysis of different epochs revealed a significant acceleration event in 2019, as can be observed in Figure 7, where certain areas of the glacier experienced peak accelerations of up to 8 meters per year².

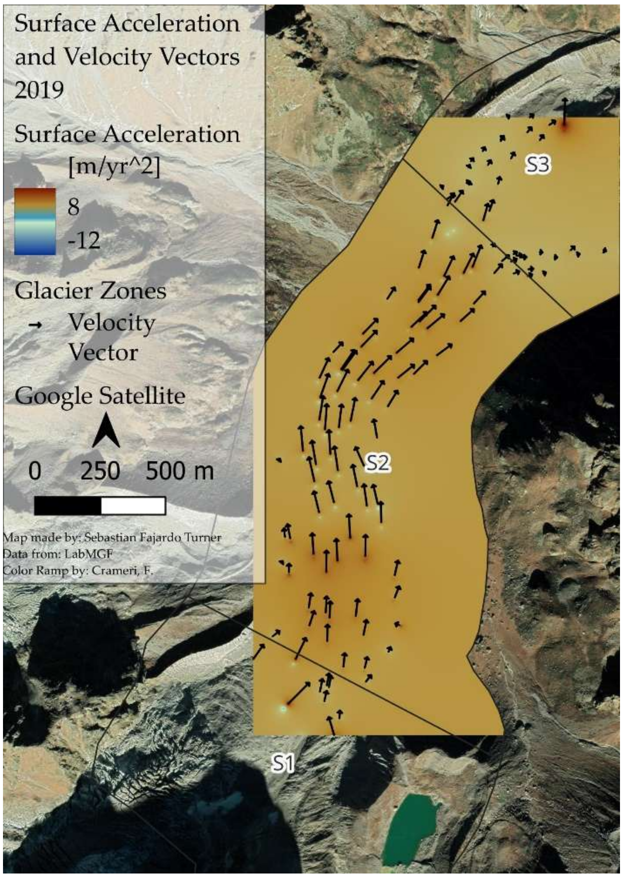


Figure 7. Example of a surface acceleration map interpolated from homologous points and GCPs in the Belvedere Glacier, 2019.

The spatial variability of glacier motion was effectively visualized through the automatically generated interpolation

maps. These maps provided critical insights into localized areas of rapid ice flow.
By incorporating these spatial patterns of movement, GlacioTools offers an efficient and easy to use tool for analyzing the evolving dynamics of the Belvedere Glacier, aiding both scientific research and hazard assessment efforts.

3.4 Automated GCP Reporting and Monograph Generation

The GCP Reporting functionalities of the plugin were tested by generating monographs for selected GCPs. An example of the module can be seen in Figure 8.

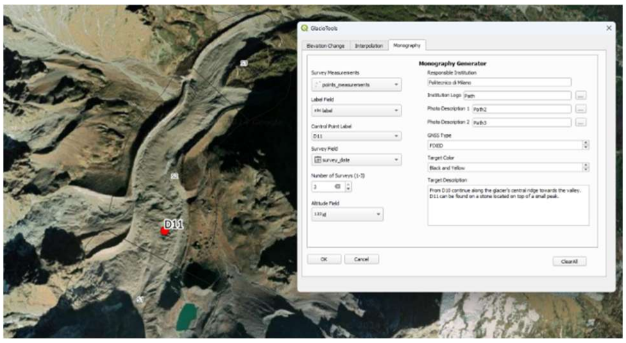
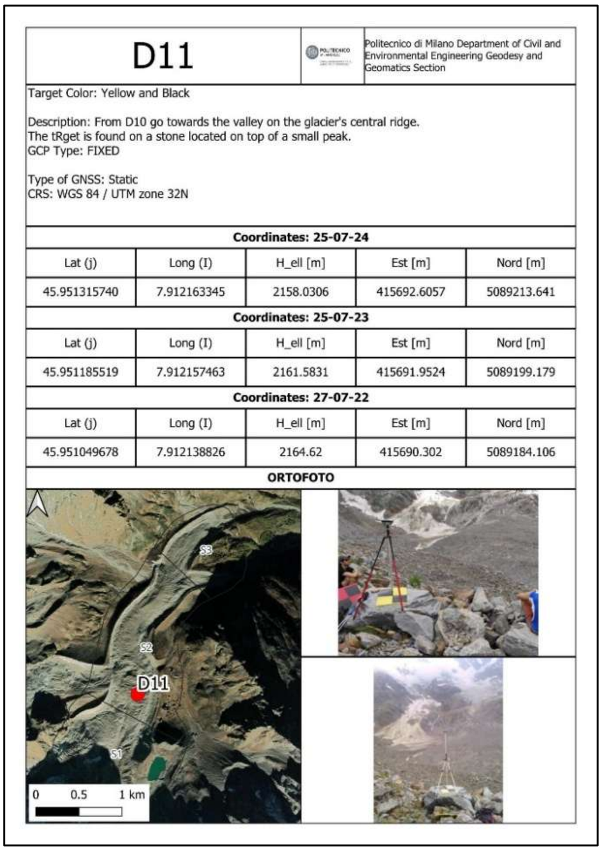


Figure 8. Example of the Monograph module of the GlacioTools plugin in the QGIS interface.

Traditionally, GCP documentation required manual compilation of tables and annotated maps, a time-consuming and error-prone task. The plugin now automates this entire process with clear and easy to use prompts, streamlining the generation of standardized GCP reports after each field survey.



D11

Politecnico di Milano Department of Civil and Environmental Engineering Geodesy and Geomatics Section

Target Color: Yellow and Black

Description: From D10 go towards the valley on the glacier's central ridge.
The tRget is found on a stone located on top of a small peak.
GCP Type: FIXED

Type of GNSS: Static
CRS: WGS 84 / UTM zone 32N

Lat (j)	Long (I)	H_ell [m]	Est [m]	Nord [m]
Coordinates: 25-07-24				
45.951315740	7.912163345	2158.0306	415692.6057	5089213.641
Coordinates: 25-07-23				
45.951185519	7.912157463	2161.5831	415691.9524	5089199.179
Coordinates: 27-07-22				
45.951049678	7.912138826	2164.62	415690.302	5089184.106

ORTOFOTO

Figure 9. Example of a GCP monograph generated with the Monograph module of the GlacioTools plugin. The document is automatically generated in the QGIS print layout as a result of the plugin processing.

Each automated report includes measured GCP coordinates for each survey epoch and annotated site photographs to aid in visually identifying GCP locations. An example of the generated monograph can be seen in Figure 9. By providing a structured and repeatable documentation process, this feature enhances data consistency across multi-year surveys and facilitates planning for future in situ campaigns, ensuring that GCP placement and recovery efforts are efficiently managed, while also streamlining the planning of future in situ campaigns. It ensures that GCP placement and recovery efforts are efficiently managed, reducing the likelihood of errors and inconsistencies. Additionally, the automated reporting process provides significant time savings compared to traditional manual methods, minimizes human error through standardized data formatting, and seamlessly integrates with PostgreSQL databases, allowing users to update reports directly from stored survey data.

4. Conclusions

The GlacioTools plugin presented in this paper streamlines glacier monitoring workflows by automating routine tasks, reducing human error, and significantly shortening the time from data collection to actionable insights. By addressing challenges inherent in traditional workflows, it enhances both efficiency and reliability. The plugin development and documentation are ongoing processes, evolving alongside the advancements in the long-term monitoring of the Belvedere Glacier. This ensures that GlacioTools adapts to new data formats and technologies employed in the research, offering a continuously refined tool that supports the project dynamic needs.
Planned future enhancements include evaluating the integration of advanced external libraries, such as Matplotlib for improved visualizations and GDAL for optimized geospatial processing. A specific focus is on the automatic generation of a model-estimated error report for the Interpolation tab. To further improve the user experience, efforts are underway to provide comprehensive documentation and submit the plugin to the QGIS Plugin Repository, making it more accessible to a wider audience. Additionally, open-source collaboration on GitHub will encourage community-driven innovation and iterative development.
The integration of InSAR (Interferometric Synthetic Aperture Radar) or DinSAR (Differential InSAR) technology is also being considered to monitor surface changes and calculate glacier surface movements. With the availability of decadal data from Sentinel-1 A, B, and the newly launched C, these advanced remote sensing techniques could complement the existing methods, offering valuable insights into glacier dynamics over time.
Beyond its research applications, GlacioTools serves as an educational platform for students, such as those involved in the Belvedere Glacier project Summer School, and as a practical, user-friendly tool for professionals. Additionally, it includes project management functionalities that facilitate the planning and execution of future surveys, making it a comprehensive solution for both monitoring and operational needs.

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