Bridging geomatics theory to real-world applications in alpine surveys through an innovative summer school teaching program

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Abstract

Teaching experience in geomatics heavily relies on hands-on activities, but field surveys for educational purposes are usually conducted in controlled environments without proper connection to real-world scenarios. Combining the widespread availability of low-cost equipment with the potential of Free and Open Source Software for Geospatial (FOSS4G) in innovative teaching programmes can fill the gap in preparing young professionals in geomatics and surveying for real-world problems and global challenges, including climate change. This paper presents the active learning experience of the Belvedere Glacier Summer School organized annually by the Department of Civil and Environmental Engineering of Politecnico di Milano in the Italian Alps. During the week-long programme of theoretical and practical sessions, students from different backgrounds, ranging from Engineering to Architecture and Geoinformatics, transform knowledge into skills by designing and carrying out surveys focused on monitoring the evolution of the glacier volume, using GNSS and UAV photogrammetry, and familiarising with 2D and 3D data processing. In a peer-led environment, participants also contribute to the production of open data (orthophotos, DSM and point measurements) published in Zenodo, fostering teamwork and collaboration not only internally but also with the wider research community.

1. Introduction

Traditionally, fieldwork activities form the basis of learning-by-doing pedagogical strategies, crafting engaging teaching methods. Particularly in the geoscience disciplines, educational activities conducted in an outdoor environment are considered a core component of students' curricula, fostering their curiosity about the subject and transforming knowledge into skills for the professional world (Thomas and Munge, 2017). The literature highlights how fieldwork manages to combine project-based learning of the target discipline with the development of social and soft skills, providing a fully transversal experience (Munge et al., 2018, Fedesco et al., 2020, Jones and Washko, 2022). Including practical activities in higher education programs plays a crucial role in knowledge transfer in geomatics too (Tucci et al., 2020, Gaspari et al., 2021). Moreover, engaging groups of students along the entire process of in-situ survey design, data collection, management, processing, and results preparation further foster their responsibility as well as the awareness of the technologies adopted, actively understanding their limitations and potentials (Balletti et al., 2023). It is remarkable that the widespread diffusion of low-cost devices allowing data acquisition for 3D model reconstruction with photogrammetry and laser scanning (Gil-Docampo et al., 2019, Ortiz-Sanz et al., 2020), while making the technology accessible to a wide variety of disciplines, increased the gap between theoretical concepts and practical application (Tucci et al., 2019). In fact, the increasing availability of open access web resources such as e-learning platforms, online manuals, webinars, massive open online courses (MOOCs) and free video tutorials has improved the accessibility of knowledge (König et al., 2012), but the lack of technical field training risks providing only superficial understanding (Vyas and König, 2014). Hence, educators are asked to design learning experiences that shift from static product-driven project-based approaches to problem or challenge-based learning, always students-centred but more dedicated to real-world applications (Carreño and Gutiérrez, 2021). Such strategies leverage learners' curiosity, teamwork and responsibility leading to the development of open-ended and inquiry-driven solutions that often stimulate the highest levels of the Bloom's Taxonomy (Botto et al., 2023): students do not only learn theoretical concepts and how to analyse results, but also how to critically evaluate the learning outcomes with their potentials and limitations (Gartner et al., 2022). With a higher level of engagement, students actively contribute to the delivery of high-quality geo-data and custom tools, contributing to long-term in-situ research projects (Potůčková et al., 2023) and delving into the advantages of the accessibility and flexibility of Free and Open Source Software for Geospatial (FOSS4G) (Ciolli et al., 2017).

In this framework, this paper presents the innovative teaching fieldwork experience carried out during the "Design and Implementation of Topographic Surveys for Territorial Monitoring in Mountain Environments" Summer School, organised by the Geodesy and Geomatics Section of the Department of Civil and Environmental Engineering of Politecnico di Milano (Italy) as part of a long-running research focused on the monitoring of glacier Belvedere in the Italian Alps (Ioli et al., 2022).

2. Context

This paper presents the innovative teaching experience annually organized on the Belvedere Glacier (Anzasca Valley, Italian Alps). The Belvedere Glacier is a low-altitude debris-covered glacier located at the east face of Monte Rosa. Its surface area is about 1.8 km^2 and its altitude ranges from 1800 to 2250 m. At its lowest point it splits into two distinct tongues (Figure 1 and Figure 2).

The Belvedere Glacier is particularly relevant among the alpine glaciers because it has experienced a very fast evolution. Until the beginning of the 21st century, the Belvedere Glacier experienced an expansion of its volume (Diolaiuti et al., 2003, De Gaetani et al., 2021). Between 2001 and 2002, the glacier was characterized by a particular surge-type dynamics (Haeberli et al., 2002). During this period, an accelerated flow in the Monte-Rosa Glacier produced a wave of compression-decompression stresses and strains in the Belvedere Glacier.

The ice thickness increased more than 20 m and the wave travelled downwards, creating a depression area in the accumulation zone, that was filled by a super-glacial lake, the Lago Effimero. After the surge event and due to the global warming effects, the Belvedere Glacier has been experiencing a very fast retreat, with an average ice thinning of ~2 m/y and a volume reduction of ~$2x10^6$ m^3 (Ioli et al., 2022). Additionally, in the past, several hazardous events originated from the Belvedere Glacier, such as floods and slope instability, threatened the nearby village of Macugnaga and the Zamboni Zappa Hut, located at 2070 m close to the glacier body (Kääb et al., 2005). Because of these reasons, the Belvedere Glacier has been widely studied in the past decades (Roethlisberger et al., 1985, Kääb et al., 2004) and is still of particular relevance among the glaciological and geomorphological communities.

Since 2015, Politecnico di Milano has carried out annual in-situ surveys, employing Global Navigation Satellite System (GNSS) and Unmanned Aerial Vehicle (UAV) photogrammetry technologies. The aim of such a decade-long research project is to obtain accurate and complete 3D models and orthophotos of the entire glacier surface, allowing the derivation of velocities and volume variations in time.

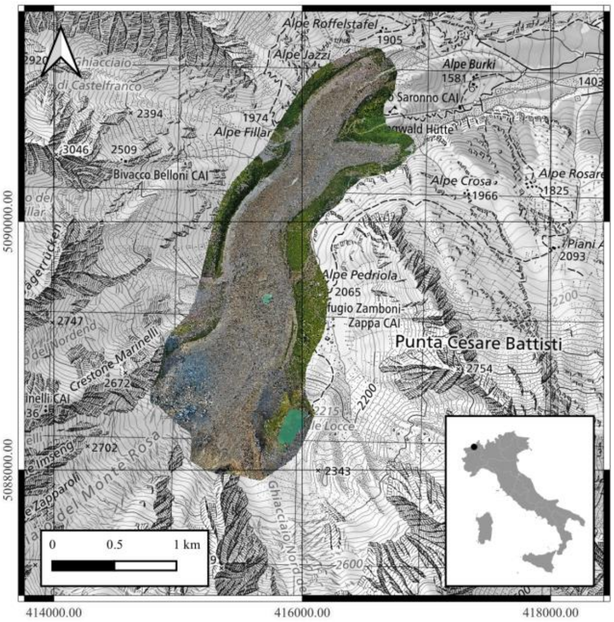

Figure 1. Map of the Belvedere Glacier in the Italian Alps with orthophoto obtained by processing the 2023 Summer School UAV photogrammetric flight. BaseMap: SwissTopo.

Figure 2. Aerial view of the Belvedere Glacier and Monte Rosa in the Italian Alps.

3. Summer School History

In the framework of the long-term Belvedere Glacier research and monitoring initiative, the Geodesy and Geomatics Section of the Department of Civil and Environmental Engineering (DICA) of Politecnico di Milano yearly organises a week-long Summer School devoted to initiate learners to the basics of geomatics surveys in challenging real environments. The innovative teaching program "Design and Implementation of Topographic Surveys for Territorial Monitoring in Mountain Environments" is intended for undergraduate and graduate students in Civil and Environmental Engineering, Geoinformatics, and Architecture of Politecnico di Milano (Figure 3). The main objective of the Summer School is to provide students with practical experience in the field of topographic land monitoring in mountain environments, a crucial topic that is often taught only in theoretical lessons, with minimal practical exercises in controlled educational contexts, often with no practical application in real-world scenarios.

Figure 3. Group picture of students and tutors who participated in the 2023 edition of the Belvedere Glacier Summer School.

The learning initiative at the Belvedere Glacier was firstly introduced in Summer 2016 and then repeated annually with the only exception of 2020, due to the Covid-19 pandemic. Since 2019, the summer school is part of the "Passion in action" initiative organized by Politecnico di Milano (https://www.polimi.it/en/programmes/innovative-teaching/).

At the end of the Summer School, students receive a certificate of attendance and are rewarded with 3 CFUs, which are officially recognised in the Diploma Supplement attached to the M.Sc. degree. For the whole duration of the practical activities, both students and tutors (research fellows and PhD students at DICA) are accommodated at the Zamboni Zappa Hut. The course is usually activated with a minimum of 6 enrolled students and a maximum of 12 are accepted, allowing a focused peer-tutoring experience. In case of overcrowding, applicants must pass an aptitude interview to be enrolled in the Summer School. In its past editions, there has been an average of 10 participants.

In 2023, the organisers initiated a process for opening data and teaching resources, while gradually moving towards free and open-source software adoption as part of the Summer School program. This on-going process was supported by the European Geoscience Union 2023 "Higher Education teaching grant" and by the Open Knowledge Foundation 2023 "Open Data Day" mini-grant (https://blog.okfn.org/2024/03/28/oddstories-2024-milan-italy/).

4. Methodology

The Summer School follows an intensive 6-days structure. The first day focuses on settling into the Zamboni Zappa Hut, transporting equipment, and introducing students to both the Belvedere Glacier environment and the Summer School program. The following 4 days constitute the program's core, integrating practical fieldwork sessions for data acquisition, theoretical lessons, and initial data exploration and processing. The final day takes place at Politecnico di Milano, and is dedicated to in-depth data analysis, followed by students' presentations of the experience and results (Figure 4).

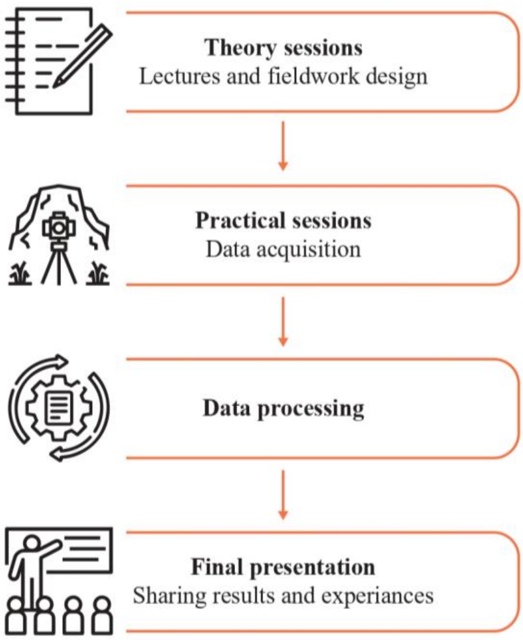

Figure 4. Organizational workflow of the Summer School learning program components.

Theory sessions, structured in 6 modules, equip students with the fundamental concepts necessary for instrument operation and field measurements (Figure 5). These sessions begin with a glaciological and geomorphological overview of the Belvedere Glacier, including its history and current kinematics. A technical session follows, covering GNSS theory and high-accuracy measurement techniques, emphasizing the differential base-rover method, necessary for surveying in internet-limited mountain environments. Next, students learn photogrammetric principles for 3D scene reconstruction from 2D images, with a focus on UAV-photogrammetry to prepare them for field data collection. Additionally, a session provides insight into the research group's long-term glacier monitoring initiatives, recent findings, and advanced short-term monitoring via fixed time-lapse cameras. Finally, students are introduced to the basics of web-based 3D visualization, learning introductory web programming concepts (HTML, CSS and JS languages) and understanding the importance of an efficient approach to data sharing and dissemination, especially for audiences not familiar with 3D geomatics products.
These theory sessions, typically lasting around an hour, are held in the evenings at the Zamboni Zappa Hut. Students are provided with open teaching materials for the sessions, ensuring continued access and reference beyond the Summer School (https://tars4815.github.io/belvedere-summer-school/).

Module	Title	Description	Software
1	Belvedere Glacier Monitoring Campaigns	Describes monitoring using UAV photogrammetry and GNSS	
2	Photogrammetry	Gives an introduction to photogrammetry	Agisoft Metashape
3	Positioning systems	Gives an introduction to GNSS positioning	
4	GIS	Gives an introduction to GIS and spatial data analysis	QGIS
5	Stereo processing	Gives an introduction on the stereo processing from fixed-time-lapse cameras	ICEpy4D Python toolkit
6	3D visualization	Defines a WebGL-based visualisation of 3D georeferenced data	Potree

Figure 5. Teaching modules for learning the basics of theoretical concepts and guiding students with tutorial on widely-adopted software for data processing.

During the four days on the glacier, students are divided into 2-3 groups, rotating through activities that take up most of the daytime. Tutors guide them throughout, ensuring a comprehensive learning experience based on a learning-by-doing approach (Figure 6 and 7). One core activity involves using a topographic-grade GNSS receiver to measure permanent targets across the glacier and its moraines. Students master setting up a fixed GNSS base station, enabling real-time corrections (RTK) via radio link for the rover receiver and also learn how to perform high-accurate RTK GNSS surveys within challenging alpine terrain, which often require to scout the moving targets within the glacier.

Another core activity is focused on UAV-based photogrammetric acquisition. Students learn to design and plan autonomous photogrammetric flights within an environment with a complex topography. They are introduced to professional-grade equipment (DJI Matrice 300 RTK and DJI P1 camera) and assist the pilot during flights. While regulations and training limitations prevent students from flying the UAVs themselves, they actively participate in flight operations.
Depending on specific needs, a final group engages in either a terrestrial laser scanner (TLS) acquisition of the glacier north

terminal lobe or in the maintenance of the existing stereoscopic camera system used for short-term monitoring (Ioli et al., 2024). This group may also assist with maintaining on-ground photogrammetric targets deployed on the glacier.

Figure 6. Tutors and students in the field during preparation of the practical activities with total station and drones.

Figure 7. Practical sessions with the execution of GNSS measurements on targets on the glacier surface and maintenance of existing fixed cameras set up.

Following daily fieldwork, students participate in a preliminary exploration of collected data (GNSS measurements, UAV images, TLS scans), including integrity checks and initial processing using specialized software packages. This exercise fosters familiarity with key data processing tools and develops the ability to critically assess fieldwork measurements.

The activities of the final day of the Summer School are carried out at Politecnico di Milano premises and consist of a more detailed data processing. Students, divided into groups and assisted by tutors, familiarize with different processing techniques. They learn to post-process GNSS measurements with software packages such as Leica Infinity and RTKlib, and calculate point displacements over time using QGIS (QGIS Contributors, 2022) by comparing current measurements with those acquired in the previous years (Figure 8). They are also asked to document survey operations in monographies for archiving. The other key component of the data processing is the 3D glacier reconstruction using Agisoft Metashape (Agisoft, 2023). Students master the entire Structure-from-Motion workflow: image orientation, GCP collimation (using field-acquired GNSS data), and dense scene reconstruction. They then use CloudCompare (Girardeau-Montaut, 2016) to analyze point clouds, estimating annual glacier reduction against previous years' data (Figure 9).

The Summer School final activity is then represented by student-led presentations. Following a peer-learning approach, groups present their fieldwork, data processing methodologies, and findings to fellow students, tutors, and attending Department professors.

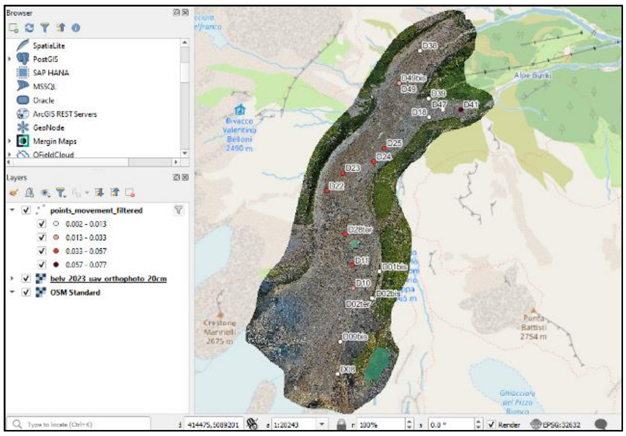

Figure 8. Setup for an exercise in QGIS environment using target measurements and orthophoto from the summer school.

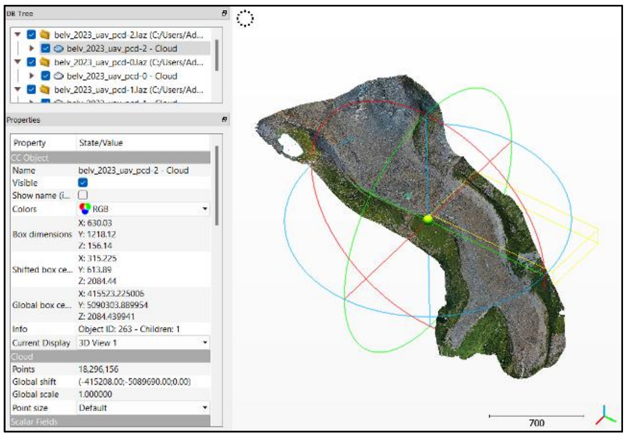

Figure 9. Visualization of the glacier point cloud in CloudCompare environment: students learn how to extract cross-sections as well as to compute distances between point-clouds of different surveys.

5. Results

Both teachers and students benefit from the implementation of the described methodology for innovative in-situ teaching. From a pedagogical point of view, teachers and tutors with an intensive summer school experience in a non-institutional environment have the opportunity to acquire a more comprehensive overview of the learning process of the participants. In fact, students can provide rapid and direct feedback, strengthening the consolidation of theoretical concepts and practical procedures, identifying and avoiding in advance misinterpretations that may occur in traditional lessons. The use of peer or near-peer strategies also helps students to develop a sense of being part of a real research programme, discovering their potential in different roles of a team. Such a sense is further reinforced by the fact that students are aware that the data they have processed and their final products, after revision by tutors, are on the way to becoming part of a dedicated version of the Belvedere Glacier open data packages on Zenodo. Knowing that their contributions will be shared with the wider scientific community and understanding the basic of a peer-review process with tutors' supervision, increases their sense of responsibility along the entire data processing activities, and promotes a sense of duty and critical thinking towards quality assurance throughout the process (Figure 10).

In addition, while improving teamwork and collaborative dynamics towards common goals, students also practice

developing and adapting problem-solving approaches in a field environment to the challenges of a real-world scenario that is constantly evolving, due to changes in the glacier and its surrounding area. For example, scouting the photogrammetric targets in the field starting from previous years' measured coordinates and monographies can also be a relevant problem that is not faced in other educational applications developed in traditionally controlled environments (Figure 11).
The opportunity for each student to interact with peers from different backgrounds, ranging from Civil and Environmental Engineering to Computer Science, helps allowing for the development of different interdisciplinary points of view on the problems and, during the final presentations, raises discussions not only on the direct experience in the field but also on the consequences and possible needs of new tools for decision-making, processing and disseminating of information related to the glacier monitoring project. It is also worth to note that a significant number of students who participated in some edition of the Summer School choose to work on specific aspects of the project during their B.Sc., M.Sc. or Ph.D. thesis.

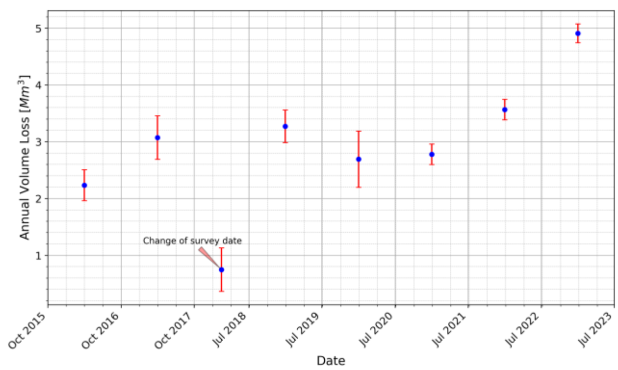

Figure 10. Glacier volume loss from 2015 to 2023 calculated using open data processed and validated in the framework of the Belvedere Glacier Summer School.

Figure 11. Participants collaborating in the field, finding solutions to real-world problems, and discussing together the best approaches.

The students' feedback, collected through a post-experience form, also showed that they felt involved, part of the group and valued at all stages of the in situ work, evaluating each teaching module with an average score of 4.6 on a scale from 0 to 5. The open responses and suggestions showed a general appreciation of the location, the management of the timing of the various activities as well as the visits to local attractions, in particular the Macugnaga museum of Walser culture, dedicated to the people who inhabited the Monte Rosa area from the XII century onwards. Such a testimony shows how the participants also managed to immerse themselves in the local culture, not limiting their experience to a technical or educational framework. On the other hand, the registration fee (100 Euros), in addition to accommodation and meal expenses, was identified as a potential barrier for students' participation that should be addressed in future editions of the Summer School.

6. Belvedere Open Data

In recognition of the value of collaboration and open science, point clouds, digital surface models (DSMs), and orthophotos for the entire glacier are published as open data under the GNU General Public License (GPL) version 3 on a Zenodo repository (Ioli et al., 2023). This open-access initiative encourages further scientific exploration and evaluation of the glacier data by researchers across disciplines, enabling the reproducibility of analysis on the glacier velocity and volume change as well as the derivation of new insights into the glacier dynamics. All data are accompanied by a structured JSON file containing essential metadata, allowing researchers to easily use the data for their purposes.

To enhance accessibility also for a non-expert audience, the 3D point clouds derived from the periodical surveys were converted to a Potree-compatible structure (Schütz et al., 2016) and uploaded to a web server. Potree is an open-source WebGL-based JavaScript library designed for web-based rendering of large-point clouds, which offers versatile tools for handling 2D and 3D objects, scene navigation, and interaction, including measurements and cross-section profile extraction (Gaspari et al., 2024, Fascia et al., 2024). With this approach, the 3D glacier models are accessible from any web browser, allowing users to navigate through different years and experience the evolution of the glacier over time (Figure 12).

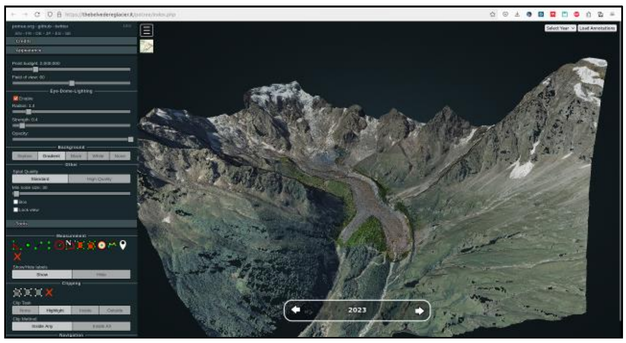

Figure 12. Web-based platform for the exploration of point-clouds, georeferenced measurements in 3D space and time based on the Potree JS open-source library.

Additionally, a robust open-source relational database (RDB) serves as the central repository for the high accuracy in-situ GNSS measurements, ensuring easy storage, use, and sharing of the data. PostgreSQL was chosen for its flexibility, permissive open-source license, and ability to seamlessly manage geospatial data through the PostGIS extension (McKenna, J. and PostGIS Team, 2021). This integration allows direct use of the glaciers data within GIS software packages such as QGIS. The database primarily serves as a repository for field survey data, including details such as survey dates, instrument specifications, key acquisition parameters, and selected processing statistics. The database currently stores 456 GNSS measurements from 85 distinct points obtained across 19 surveys. Also, the measurements can be queried and visualised in a GIS environment, enabling automatic plotting of points associated with each measurement on a map canvas, together with pre-defined visualization styles, facilitating visual analysis and interpretation. Moreover, both researchers and non-expert users can access the public schema of the database via a dedicated web platform (https://thebelvedereglacier.it/). Here, users can effortlessly view the GNSS measurements on a web-map, extract time-series information, and download them for their scientific purposes (Figure 13). Combining this with a web-based visualization of the 3D point clouds with Potree makes it possible to have a complete overview of the outcomes of the Belvedere Glacier monitoring campaign.

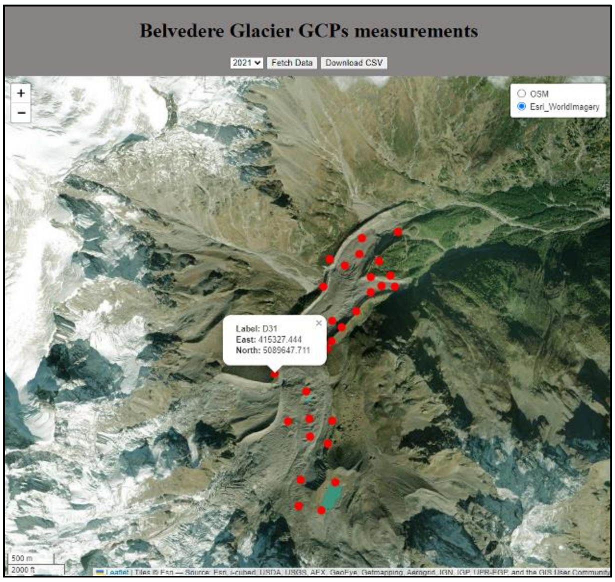

Figure 13. Interactive web-map for exploring and downloading targets measurements over time, based on Leaflet JS.

7. Conclusions ad future development

The Belvedere Glacier Summer School, part of an ongoing decade-long research project, aims to promote geomatics education at university level through a real-world application. The core elements of the latest editions of the Summer School are peer-led practical field sessions, openly accessible teaching materials and student contribution to open data preparation. While putting theoretical concepts of photogrammetry, GIS and GNSS into practice, participants also develop complementary skills for their professional preparation, ranging from critical thinking about data quality, to teamwork with role responsibilities, to understanding shared and open knowledge.

The teaching resources published on the MkDocs website allow for continuous updating of the course content, ensuring that the materials are available after the Summer School period and for students who wish to be prepared on the topics discussed. The modular structure is regularly reviewed with the aim of making it as comprehensive and accessible as possible, taking into account the transition to full FOSS4G software adoption: in fact, alternatives to Metashape for the photogrammetry module are currently being evaluated (e.g. OpenDroneMap and Meshroom). The open data publication and documentation is also intended to become a best practice for the next generation of researchers interested in studying the evolution of the glacier in the long term, providing an insightful starting point for possible future interdisciplinary teaching or research projects with pre-processed data to be used for environmental system modelling, simulations and more.

For the future, the Summer School organisers are considering effective strategies to make this learning experience fully open and accessible. In particular, the introduction of Virtual Reality is currently under study. Such an approach would allow the participants to be better prepared in advance, gaining prior knowledge of the site through first-hand virtual exploration (Bos et al., 2022). Most importantly, it could be exploited to engage a wider audience, designing shared virtual and inclusive field experiences that can overcome cost and mobility constraints (Chiarella and Vurro, 2020, Paulsen et al., 2024).

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