# Glacier Instabilities Identification and Monitoring: Case Studies in the Alps

Daniele Giordan[1*]

[1]Italian National Research Council, Research Institute for Geo-Hydrological Protection, Turin, Italy

(*Corresponding E-mail: daniele.giordan@cnr.it)

**Abstract: Monitoring glacier instability is essential for assessing geo-hydrological hazards in mountain regions. This study reviews monitoring systems based on measurement type and data acquisition frequency, emphasizing their role in early warning. Instruments range from single-measurement and multi-temporal methods to near-real-time and real-time networks. Combining topographic, geophysical, and meteorological monitoring enhances reliability through redundancy and cross-validation. Low-cost technologies, including open-access satellite data, webcams, drones, and Raspberry-Pi systems, expand spatial coverage at reduced costs. Integrated, multi-sensor networks represent a scalable and cost-effective approach to detecting instability and improving risk management in rapidly changing alpine environments.**

**Keywords:** ***Glacier instabilities, Monitoring.***

## Introduction

Monitoring glacier instabilities is a key component in understanding and mitigating geohydrological hazards in high mountain environments. Over recent decades, a wide range of monitoring systems has been developed to capture the complex dynamics of glacial and periglacial processes. However, the classification of these systems remains non-univocal, as instruments differ in their measurement principles, temporal resolution, and operational purposes. This paper presents an overview of monitoring systems based on the physical quantity measured and the frequency of data acquisition, emphasizing their role in early warning and risk mitigation. A specific focus is given to low-cost technologies, which are increasingly relevant for expanding monitoring coverage in remote alpine areas.

## Monitoring Systems and Data Acquisition Frequency

The frequency of data acquisition is a fundamental parameter for evaluating the suitability of a monitoring system to describe the evolution of instability processes. An insufficient sampling frequency may prevent the detection of precursor signals, while an excessively high frequency may result in data redundancy and resource inefficiency. Defining an optimal operational range is therefore essential to ensure both data quality and cost-effectiveness. Monitoring systems can be categorized according to increasing temporal resolution:

**Single-measurement systems** provide one-time characterization of the phenomenon, often within dedicated field campaigns.

**Multi-temporal systems** operate at low update frequencies (e.g., semiannual or annual) and are useful for long-term trend analysis, such as with aerial or satellite imagery.

**Near-real-time systems** offer frequent updates with limited processing delays, allowing the observation of dynamic processes with acceptable approximation.

**Real-time systems** ensure negligible latency between acquisition and data availability, supporting both early warning and alarm applications.

## Monitoring Parameters and Techniques

Monitoring systems can also be classified according to the **physical variables** they measure. Topographic variations are among the most commonly observed parameters, detected through techniques such as radar and optical remote sensing, LiDAR surveys, ground-based synthetic aperture radar (GBSAR), and topographic instrumentation (Dematteis et al., 2017). These systems enable the quantification of surface displacements over time, providing crucial input for kinematic and stability analyses.

To complement surface observations, **inclinometric systems** are employed to investigate subsurface movements, offering three-dimensional insights into slope deformation patterns. While widely used for landslide monitoring, these instruments are also applicable to rock glaciers and other frozen-slope processes.

**Geophysical systems**—including ground-penetrating radar (GPR) and seismic sensors—enable the investigation of glacier internal structures and debris-flow detection, respectively. Additionally, **meteorological variables** (temperature, precipitation, radiation) play a vital role in interpreting the climatic forcing driving glacier instability, especially under ongoing climate change conditions (Dematteis et al., 2022b).

## Integrated and Redundant Monitoring Networks

A robust monitoring network typically combines multiple sensors and measurement approaches. Multi-instrumental networks allow cross-validation of independent measurements, enhancing reliability and providing redundancy—a critical feature in early warning systems (Figure 1). High-frequency sensors are integrated with optical or visual monitoring tools, such as remote cameras, enabling near-real-time visual assessment of evolving conditions. Such redundancy ensures continuous data acquisition improving the overall resilience of the monitoring network.

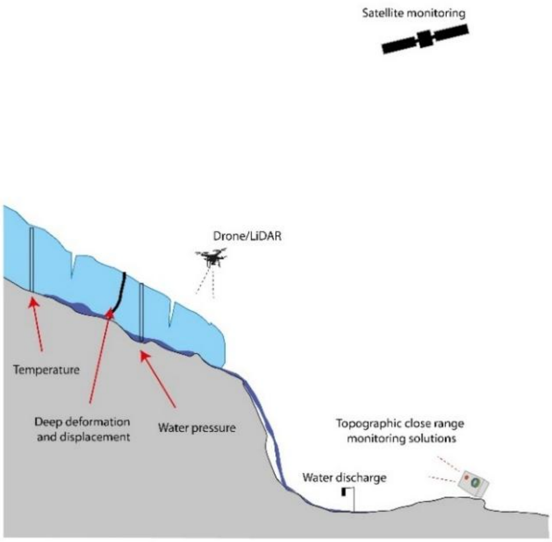


*Figure 1, Examples of glacier monitoring solutions.*

## Low-Cost Monitoring Technologies

The growing demand for extensive spatial coverage and cost-effective solutions has fostered the adoption of **low-cost monitoring systems**, particularly valuable in alpine and glacial environments. These include both satellite-based open-access data and terrestrial imaging systems.

**Satellite systems** such as ESA's Sentinel and NASA's Landsat missions provide freely available multispectral imagery with revisiting times of 5–8 days, enabling the detection of surface changes at various spatial resolutions (10–100 m). Private constellations such as PlanetScope and Maxar further increase temporal resolution, offering near-daily coverage with 3 m ground resolution, supporting both scientific research and civil protection applications (Dematteis et al., 2022a). Radar data from Sentinel-1 further enables interferometric deformation mapping via the European Ground Motion Service.

**Terrestrial low-cost tools** include webcams, digital cameras, and Raspberry-Pi-based imaging modules (RaspiCam). Webcams are robust and easy to install, often enabling remote control and automated image acquisition, whereas DSLR and mirrorless cameras allow greater optical flexibility and higher photogrammetric quality. RaspiCam systems represent an ultra-low-cost solution (<50 €), offering high control flexibility through open-source software, though their reliability for early warning remains under evaluation (Ioli et al., 2024; Giordan et al., 2016). Drones (UAVs) complement these systems by capturing high-resolution imagery and digital terrain models (DTMs) in inaccessible areas. GNSS-RTK-equipped multirotor systems enhance spatial accuracy, though high-altitude conditions pose challenges for flight stability and battery performance.

## Discussion and Conclusions

Monitoring glacier and periglacial instability requires multi-scale, multi-sensor data to capture surface and subsurface deformation over time. Effective early warning systems depend on sensor precision, acquisition frequency, network robustness, and the ability to process large datasets in near-real time. Combining low-cost technologies with open-access satellite data enables scalable, cost-effective monitoring networks that enhance spatial coverage and support both research and risk management. Continued development and field validation are key to ensuring their reliability within glacier hazard early warning frameworks.

## References

Dematteis, N., Giordan, D., and Crippa, B., Monserrat, O. (2022a). Fast local adaptive multiscale image matching algorithm for remote sensing image correlation. Computers and Geosciences, 159, 104984. https://doi.org/10.1016/j.cageo.2021.104988

Dematteis, N., Giordan, D., Perret, P., Grab, M., Maurer, H., and Troilo, F. (2022b). Evidences of bedrock forcing on glacier morphodynamics: A case study in the Italian Alps. Frontiers in Earth Science, 10, 793546. https://doi.org/10.3389/feart.2022.793546

Dematteis, N., Luzi, G., Giordan, D., Zucca, F., and Allasia, P. (2017). Monitoring Alpine glacier surface deformations with GB-SAR. Remote Sensing Letters, 8 (10), 947–956. https://doi.org/10.1080/2150704X.2017.1335905

Giordan, D., Allasia, P., Dematteis, N., Dell'Anese, F., Vagliasindi, M., and Motta, E. (2016). A low-cost optical remote sensing application for glacier deformation monitoring in an Alpine environment. Sensors, 16(10), 1750. https://doi.org/10.3390/s16101750

Ioli, F., Dematteis, N., Giordan, D., Nex, F., and Pinto, L. (2024). Deep learning low-cost photogrammetry for 4D short-term glacier dynamics monitoring. PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science. https://doi.org/10.1007/s41064-023-00272-w