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# Development of guidelines for monitoring snow-ice fed mountain streams. The IdroStelvio network (Stelvio National Park, Italy)

**Abstract:** Bocchiola D., Stucchi L., Fugazza D., Alborghetti M., Almagioni C.D., Azzoni R.S., Barbagallo, B., Bernasconi D., Compostella C., Dezuanni P., Ferrarin L., Morgese S., Pedrotti L., Traversa G., Verza G.P., Senese A., Diolaiuti G.A., *Development of guidelines for monitoring snow-ice fed mountain streams. The IdroStelvio network (Stelvio National Park, Italy).* (IT ISSN 0391-9838, 2025). We present the main outcomes of the IdroStelvio project, a continuous (2010-present) monitoring initiative developed through cooperation between the Stelvio National Park Authority, the University of Milano, and Politecnico di Milano. The project established and maintained a hydrometric network monitoring 11 high-altitude streams predominantly fed by snow and ice meltwater. The monitoring system, covering approximately 32% of the park's area, and more than 90% of glacierized catchments therein, provides a comprehensive view of the hydrological dynamics of this sensitive Alpine region. IdroStelvio represents one of the most extensive and long-standing case studies of hydrological monitoring in glacierized environments, both in Italy and internationally. Beyond reporting the structure, evolution, and scientific outputs of the network, this paper distills the operational experience gained into a set of practical guidelines for the monitoring of snow-ice fed mountain streams. These guidelines address site selection, sensor configuration, maintenance protocols, and data validation strategies, aiming to support the replicability of similar systems in other high-altitude regions. The collected data are valuable for glacio-hydrological modeling, scenario analysis, and water resource planning under climate change. The IdroStelvio experience may serve as a reference framework for future monitoring initiatives in sensitive alpine environments.

**Key words:** Alpine streams, Mountain hydrology, Cryosphere, Hydrometric stations.

**Riassunto:** Bocchiola D., Stucchi L., Fugazza D., Alborghetti M., Almagioni C.D., Azzoni R.S., Barbagallo, B., Bernasconi D., Compostella C., Dezuanni P., Ferrarin L., Morgese S., Pedrotti L., Traversa G., Verza G.P., Senese A., Diolaiuti G.A., *Sviluppo di linee guida per il monitoraggio dei torrenti di montagna alimentati da fusione nivo-glaciale. La rete IdroStelvio (Parco Nazionale dello Stelvio, Italia).* (IT ISSN 0391-9838, 2025). In questo studio presentiamo i principali risultati del progetto IdroStelvio, un'iniziativa di monitoraggio continuo avviata nel 2010 e tuttora in corso, sviluppata grazie alla collaborazione tra l'Ente Parco Nazionale dello Stelvio, l'Università degli Studi di Milano e il Politecnico di Milano. Il progetto ha istituito e mantenuto una rete idrometrica che monitora 11 torrenti d'alta quota, alimentati prevalentemente da neve e acqua di fusione glaciale. Il sistema di monitoraggio, che copre circa il 32% della superficie del parco e oltre il 90% dei bacini glacializzati presenti, offre una visione completa delle dinamiche idrologiche di questa regione Alpina. IdroStelvio rappresenta uno dei casi studio più estesi e duraturi di monitoraggio idrologico in ambienti glacializzati, sia in Italia che a livello internazionale. Oltre a descrivere la struttura, l'evoluzione e i risultati scientifici della rete, questo articolo sintetizza l'esperienza operativa acquisita in una serie di linee guida pratiche per il monitoraggio dei torrenti montani alimentati da neve e ghiaccio. Queste linee guida riguardano la selezione dei siti, la configurazione dei sensori, i protocolli di manutenzione e le strategie di validazione dei dati, con l'obiettivo di supportare la replicabilità di sistemi simili in altre regioni d'alta quota. I dati raccolti sono preziosi per la modellazione glacio-idrologica, l'analisi di scenari e la pianificazione delle risorse idriche in un contesto di cambiamento climatico. L'esperienza di IdroStelvio può servire da quadro di riferimento per future iniziative di monitoraggio in ambienti alpini sensibili.

**Termini chiave:** Torrenti alpini, idrologia di montagna, criosfera, stazioni idrometriche.

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## INTRODUCTION

We present here the main results of the IdroStelvio project, launched in 2010 through the cooperation between the Stelvio National Park Authority, the University of Milano, and the Politecnico of Milano, and renewed several times since then. After 15 years of continuous activity, the network has delivered valuable scientific results. The data thereby collected served as a basis for numerous Master and PhD theses (e.g. Stucchi, 2023).

Stelvio National Park is home to many of the main glaciers in Italy (Diolaiuti and Smiraglia, 2010; D'Agata *et al.*, 2014).

In Europe, and more specifically in Italy, streamflow measurements in mountain areas are limited (Bocchiola, 2014; Bertola *et al.*, 2020). The high slope of mountain streams, the high turbulence, and diffuse phenomena of erosion and sedimentation, make it difficult to find a proper location for measurements. Moreover, frequent floods and extreme weather, such as low winter temperatures, constantly threaten the hydrometric stations, which are made by delicate materials.

For these reasons, besides a few operated high-altitude lakes (generally artificially created for hydropower purposes), hydrological regimes are mostly unknown (if not via modeling). Thus, designing, implementing, and maintaining the IdroStelvio network has had, and still has, timely and far-reaching impacts. The network further represents a virtuous instance of joint action between a public institution (Park Authority) and academic partners, aimed at increasing hydrological knowledge and assessing future water availability. The specific goal of the project is to monitor and quantify water resources, as a basis to validate hydrological conjectures, such as assessments of water supply and dynamics from different environmental compartments (liquid water from rain, snow/ice melt, and permafrost whenever present) within the park, both to safeguard this natural resource and to support ecological studies and ecosystem management. In addition to presenting the structure and outcomes of the IdroStelvio network, this paper aims to propose a set of practical guidelines for the monitoring of snow-ice fed mountain streams. These guidelines, derived from field-tested procedures and adaptive strategies, are intended to support the replicability of similar monitoring systems in other high-altitude environments.

## STUDY AREA

### *Stelvio National Park*

Stelvio National Park spans an area of 130,700 hectares in the heart of the Central Alps, and it is a typical high-altitude mountain park. Approximately three-quarters of the park are located above 2,000 m a.s.l. (see Figure 1), reaching a highest peak elevation of 3,905 m a.s.l., at the summit of Mount Ortles. Due to its average high elevation, the park displays a tapestry of rugged peaks and extensive glacier areas. The Ortles-Cevedale group, located on the border between Lombardy and Trentino-South Tyrol, forms the geographical core of the park.

The bedrock is mainly composed of metamorphic rocks (Gneiss, Phyllite, Mica Schists), with minor occurrences of igneous rocks (Granites). Uniquely in the inner Alps, the northwestern sector of the park features sedimentary carbonate rocks (primarily Dolomite). Valley floors are covered with hay-pastures, while higher slopes host conifer forests. At higher altitudes, alpine grasslands take over (Casale and Bocchiola, 2022), including Dwarf Heath and Grey Alder bushes, becoming increasingly sparse with elevation, and eventually yielding to snowbeds, where few plant species survive. Eventually, higher elevation areas with rocks and debris host rock thriving plants (Alpine dandelion, *papaver rhaeticum*). The climate of the area is strongly dependent on the altitude. At high elevations, winter is characterized by low air temperatures (well below -20°C), but during the summer season, due to climate change air temperature can reach up to +15°C at the surface of the glacier, inducing massive melting (Senese *et al.*, 2012, 2014, 2018). The park is home to more than 260 vertebrate species. Particularly noteworthy is the presence of large birds of prey, such as Golden Eagle and Bearded Vulture (Pedrini and Volcan, 2017), rich populations of ungulates (especially Red Deer and Alpine Ibex), and several species typical of the alpine habitat (including several grouse species, marmots, mountain hares, and stoats). Invertebrates also thrive here, often in extreme environments, like the glacier surface itself (Crosta *et al.*, 2025).

In addition to its natural wealth, Stelvio Park is rich in history. During World War I, it marked the western end of the combat front between Italy and Austria. Numerous traces of these tragic events, the so-called "White War", still remain visible, particularly in the Braulio Valley, Stelvio Pass, Forni Valley, and Gavia Valley, under the form of military roads, mule tracks, trenches, and alpine villages (Morosini and Ingold, 2022).

Established on April 24, 1935, Stelvio National Park was initially managed by the State Forestry Agency, and the State Forestry Corps. During 1995-2015, the Park was administered by a consortium including the Italian State, the Lombardy Region, and the autonomous provinces of Trento and Bolzano. With the enactment of Legislative Decree No. 14 (January 13, 2016), the consortium was dissolved, and administrative functions were delegated to the respective autonomous provinces and the Lombardy Region. The Lombardy section is now managed by ERSAF (Regional Agency for Agriculture and Forestry Services). A dedicated coordination and steering committee ensures the park's overall unity of management. Surveillance is carried out by the Carabinieri Forest Service in Lombardy, and by provincial forest corps in Trento and Bolzano. The park territory covers 23 municipalities, ten in Lombardy, ten in the Province of Bolzano, and three in the Province of Trento.

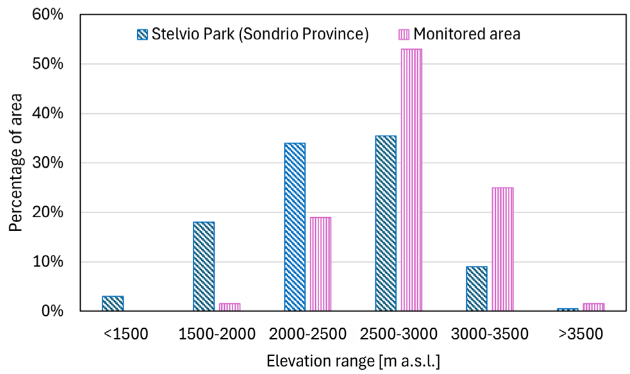


Figure 1 - Relative distribution of the altimetry (expressed as percentage over the total area) within Stelvio National Park area and monitored area.

*The IdroStelvio Network*

The IdroStelvio hydrometric network was established in 2009, and installations began in 2010 (see Figure 2). Initially (July 2010), two stations were installed in the Gavia Valley (named Gavia Valle and Gavia Alpe), one on the Cedec stream near the mouth of Val Cedec (Forni Cedec), and one on the Frodolfo stream in Forni Valley (Forni Valle). The network was expanded in June 2011, with three more stations on the Braulio stream (Braulio Stelvio, Braulio Monte, and Braulio Valle), one additional station on the Gavia stream (Gavia Monte), and two more stations on the Frodolfo (Forni Monte and Forni Rosole). In 2013, an eleventh station was added, in the Zebrù Valley.

Today, the network monitors four of the most significant valleys in the park, covering approximately 32% of its total area. Glacierized surfaces are monitored for 92%. As of 2025, ten stations are active: three in the Braulio Valley, two in the Gavia Valley (Gavia Valle station was dismantled in 2014), four in the Forni Valley, and one in the Zebrù Valley.

The New Italian Glacier inventory published in 2015 and revised in 2016 (Smiraglia *et al.*, 2015; Diolaiuti *et al.*, 2019) recorded 82 glaciers within the park, covering about 5% of its total area, with an average size of 0.37 km². Notably, 78% of these glaciers are located within the monitored catchments. A summary of the IdroStelvio stations, including location, catchment area, installation date, and presence of upstream reservoirs and water withdrawal is provided in Table 1.

[redacted]

*Status and maintenance of IdroStelvio network*

Due to the extreme climate conditions of Stelvio Park, where the stations face alternatively freezing, flash floods, severe sediment transport, and landslides, the safeguard of the operativity of the stations represents a main challenge for the researchers. Owing to the lack of proper facilities and specialized manpower, the stations are often installed in precarious environments. When available (Gavia Alpe, Forni Valle, Forni Cedec, Forni Monte, Zebrù, Braulio Monte) the stations are anchored to a bridge, to guarantee their security and facilitate accessibility. In the other cases, they are fixed to large rocks or boulders. The stations are made up by a box containing a data logger featuring low power consumption (models E-Log, M-Log and Alpha-Log by LSI LASTEM), a sealed 12 V lead-acid battery, and a solar regulator, which modulates solar energy captured by the panel on the front of the box and keeps the battery charged. In all but one station, a cell piezometer, connected to the data logger, is anchored to the riverbed by a rubber tube, which also protects the sensors from rocks and sediments. In one station, Forni Monte, a radar sensor is instead used to measure water level from the body of the bridge without direct contact with water. Piezometers used

Table 1. Features of the stations of the IdroStelvio network.

| Valley | Station | Watershed [km²] | ID | Stream | Installation date | Elevation [m a.s.l.] | Upstream pipelines |
|---|---|---|---|---|---|---|---|
| Gavia | Monte | 19.12 | GM | Gavia | 22/06/2011 | 2234 | no |
| | Alpe | 8.06 | GA | Alpe | 16/09/2010 | 2289 | no |
| | Valle | 35.22 | GV | Gavia | 27/07/2010 | 1734 | yes |
| Forni | Valle | 67.36 | FV | Frodolfo | 17/09/2010 | 1762 | yes |
| | Cedec | 17.63 | FC | Cedec | 16/09/2010 | 2218 | no |
| | Monte | 17.63 | FM | Frodolfo | 20/06/2011 | 2211 | no |
| | Rosole | 7.11 | FR | Rosole | 20/06/2011 | 2457 | no |
| Braulio | Valle | 24.75 | BV | Braulio | 21/06/2011 | 1842 | yes |
| | Monte | 9.64 | BM | Braulio | 21/06/2011 | 2264 | no |
| | Stelvio | 0.66 | BS | Braulio | 25/07/2011 | 2506 | no |
| Zebrù | Zebrù | 30.14 | ZB | Zebrù | 11/06/2013 | 1920 | yes |

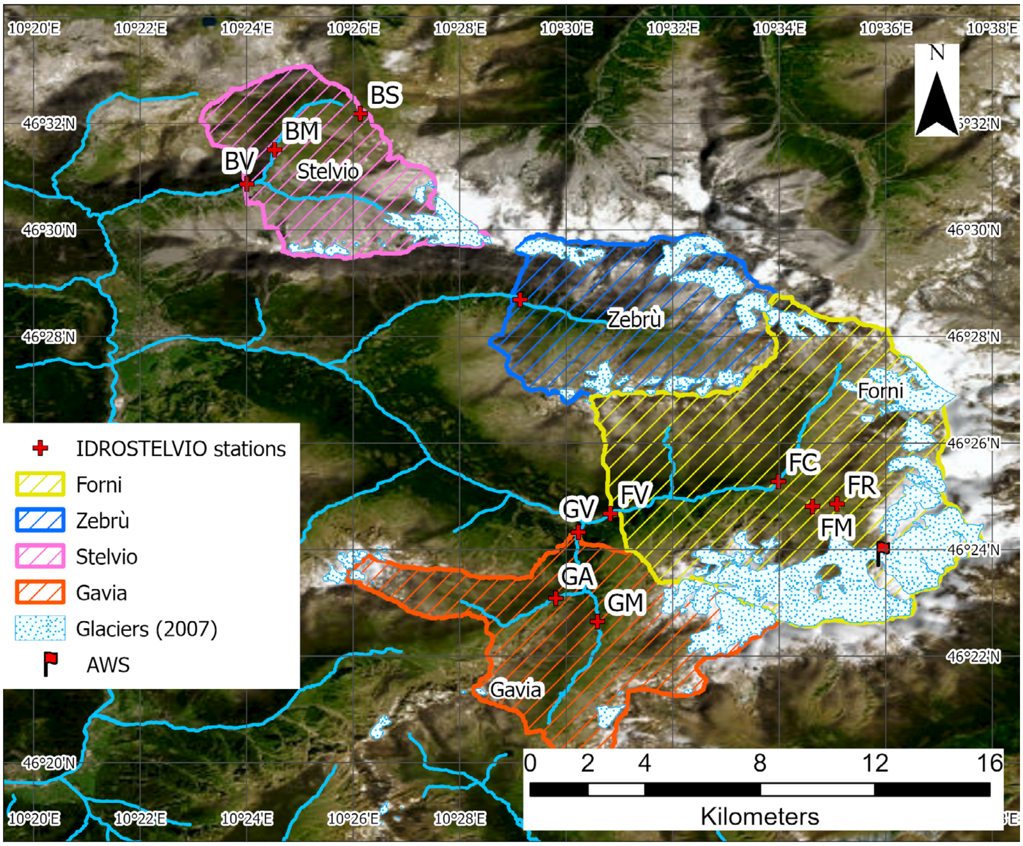


Figure 2 - The IdroStelvio network. The main stream network is reported together with the monitored basins, hydrometric stations, glacier extension in 2007, and Forni Glacier Automatic Weather Stations. BV = Braulio Valle, BM = Braulio Monte, BS = Braulio Stelvio, FV = Forni Valle, FC = Forni Cedec, FM = Forni Monte, FR = Forni Rosole, GV = Gavia Valle, GA = Gavia Alpe, GM = Gavia Monte. Reference system: WGS84.

over the years measure water depth in the range 0-3 m or 0-10 m, with a stated uncertainty of 0.25%; the radar sensor measures distance in the range 0-8 m with a reported accuracy of 5 mm. In order to protect the batteries and the sensors from freezing water, the stations are generally wintered in fall and activated through spring and summer time. Through the years, it was observed that some stations received enough sunlight to stay active during the winter, so they were maintained to try to measure the whole snow melt season.

However, the stations have faced several malfunctioning accidents and recovering reliable data has not always been possible. Recurring accidents are represented by: i) burial of the sensors by debris, which often times led to the destruction of the sensor itself, ii) loss of elasticity of the sensor membrane, leading to the loss the correspondence between measured pressure and water level, iii) electrical fault, due to humidity entering the data logger, iv) mechanical failure of the stations due to snow load, v) loss of stored data, which happens when it is not possible to access the stations for extended periods of time (e.g. during the COVID-19 outbreak, lasting spells of bad weather, road blockages owing to landslides) leading to the saturation of the memory. Moreover, on 28 August 2023 (ANSA, 2023), the stations faced a major rainfall event, leading to floods in the downstream municipalities, and the collapse of one station, Forni Monte, and loss of corresponding data. The station was replaced in summer 2024, taking back the number of active stations to 10. In Figure 3 some representative stations are reported.

### *Water stage data*

The raw data collected by the network stations (water depth, measured by a piezometric device, then corrected using a measured offset) require correction before use, in order to filter out noise. These stations operate in harsh alpine conditions, which makes it crucial to understand their limitations and issues related to data quality. If a measurement cannot be taken owing to sensor or data logger failures, the data logger identifies the critical situation and assigns a "NO DATA" flag. In other cases, even if data have been recorded, the values can be unrealistic or unacceptable. While "NO DATA" entries are easy to identify and filter out, detecting anomalous data is more challenging.

Such issues were tackled, and the authors identified some major problems affecting the data:

1) Extremely low temperatures can cause freezing of water inside the sensor, resulting in abnormally high pressure readings.
2) During thawing periods, erroneous water level readings may occur, possibly due to mixed water/ice conditions, and/or exchanges of heat/energy fluxes.


Figure 3 - Four representative stations of IdroStelvio network: a) the highest altitude station, Braulio Stelvio, monitoring the smallest stream, ca. 1 m wide, b) Zebrù station, located in a low slope area, allowing safe measurements of geometry and discharge, c) Forni Cedec station, located in a very steep area, where discharge measurements are made difficult by turbulence, d) Forni Monte station, downstream Forni glacier, where the discharge regime is strongly related to air temperature in summer.

3) Snow accumulation on solar panels disrupts power supply, possibly leading to shut down of the station.
4) Over time, the piezometric membrane may lose elasticity, producing biased readings (e.g., recording a non-zero level even in dry conditions).
5) The devices are sometimes displaced during winter maintenance, to avoid damage from freezing. However, restoring them to the exact original position is difficult, possibly generating problems with the offset (however re-assessed at each new installation).

The preliminary data processing procedure may address the first and second problem. The third problem is less easily coped with, due to the lack of real-time information on snow cover at each site. Proper positioning of the solar panel may however help. To address the issue of low temperatures, we identified -5°C as a critical threshold: water level data recorded below this temperature are automatically discarded. For each site, a "physically acceptable" maximum water level was also defined, based on the geometry of the cross-section and upstream catchment. To test device functionality, during *in situ* surveys, whenever the discrepancy between field measurements and device readings exceeds a pre-defined threshold (approx. 10 cm), the logger is considered unreliable and replaced.

Besides semi-automatic assessment (e.g. temperature and highest water levels), all data series are however also visually checked out for consistency. This procedure helps produce a first-stage time series of water levels. Subsequently, stream flow estimates are obtained, using stage-discharge curves, continuously updated for the river sections of interest.

## STAGE DISCHARGE CURVES

Tuning of stage discharge curves, or flow stage-discharge (*h*-*Q*) equations, is carried out periodically for each of the stations. Given the dynamic nature of the investigated mountain streams, possibly subject to modifications given by sediment transport and deposition, stage discharge equations are re-assessed at least once per year, and whenever necessary in the wake of important flood events.

A river wading approach is pursued, and the area-velocity method is adopted. Cross stream water depth is evaluated by wading rods and tape measurements, and flow velocity is measured using a 3D doppler velocimeter (using the flow-wise velocity component in planar direction). At least ten measuring spots are measured for each cross-section survey, distributed as evenly as possible. Given the generally low water stage during wading ($h \leq 0.3$ m ca.), only one flow velocity test is performed (ca. half depth). However, for deeper flows, a further measuring point is added every 0.3 m ca. (i.e. 2 measures for $0.3 \leq h \leq 0.6$ m ca., and 3 measures for $0.6 \leq h \leq 1$ m ca.). Very rare, if any, measurements are taken for $h > 1$ m, given the nature of the small streams, and the somewhat high river slope and flow velocity.

Whenever possible, *h-Q* measurements are made at least twice every year in each section, to explore different flow depth values (i.e. low flow/high flow season).

The *h-Q* equations are then cast by a reasoned mix of i) use of hydraulic laws (e.g. Manning's Equation), and ii) interpolation of the observed *h-Q* pairs, the latter especially for sections with a large number of *h-Q* pairs, and/or acceptable stream stability in time.

### *Hydrological modelling*

The discharge data collected and presented here, along with meteorological and snow-glacier data collected by the authors or provided by other agencies, have been used to model the hydrology of the catchments and the Park area in general.

The glacio-hydrological model used is the well-established Poli-Hydro (Groppelli *et al.*, 2011; Soncini *et al.*, 2017; Stucchi *et al.*, 2019), which was suitably modified and calibrated for the hydrological and climatic characteristics of the park in a recent PhD thesis (Stucchi, 2023).

Poli-Hydro is a semi-distributed hydrological model, based on a 25 m resolution Digital Elevation Model of the catchment area. Such a high resolution allows a correct spatialization of glacier outlines, air temperature, and snow to rain partition. The model proved reliable in reproducing river discharge at monitored sites and allowed estimation of runoff.

Moreover, the model can partition runoff into its expected components, such as rainfall, snowmelt, and glacier melt – an important aspect for understanding how the cryosphere responds to climate change

## RESULTS

### *Data completeness and IdroStelvio status*

This section presents summary statistics, based on the water level data collected at each hydrometric station since their installation. Tables 2 and 3 report the (number of) daily readings per month/year, for each station. Several stations are inactive during winter due to their elevation, resulting in low data availability during these months. Even when functioning, sensors may record near-zero water levels, due to freezing conditions, or they may be obstructed by snow/ice. These data clearly provide insights into the operational challenges of maintaining monitoring infrastructure in an extreme alpine environment. Periods of missing data are typically explained in yearly reports, and are generally due to equipment failure, damage to sensors or data loggers, or in some cases floods and/or vandalism.

Despite these difficulties, a satisfactory level of data completeness was generally achieved, particularly considering the demanding environment. When long gaps in data occur at stations without significant upstream regulation, missing flows can be reconstructed using hydrological modeling, as demonstrated in the following.

Some stations present greater challenges. For example, the Forni Monte station - located near the Forni Glacier's ablation tongue - experiences large summer flows and sediment transport during the melting season. The piezometric device was damaged in 2013 and since then replaced by a radar sensor. In the subsequent years, a number of technical problems have made measurements very challenging here. Nevertheless, this station is of the utmost importance to gather information about melting of Forni glacier, one of the largest in the Italian Alps.

Other stations have been affected by vandalism or extreme flood events. Braulio Stelvio was damaged in 2013 and only restored in 2019. As mentioned, Gavia Valle station, the first to be installed, was decommissioned in 2014 due to safety concerns, caused by sudden upstream water and sediment pulses.

While occasionally problematic, the IdroStelvio network has thus far delivered a valuable dataset. The experience gained here allowed us to identify critical stations, where replacing submerged sensors with radar instruments should be advisable for robustness and reliability.

### *Observed discharge regimes*

Data of measured discharge for each hydrometric station are reported in Supplementary figs S1-S12. The long-term dataset and experience gained through network operation allow for relevant scientific and technical insights. Scientifically, the data confirm that discharge regimes for glacier-fed streams are more closely tied to air temperature than those fed solely by rainfall. Notably, even during the severe drought of 2022 that affected much of Italy, glacier-fed stations recorded higher-than-average summer flows, highlighting the buffering role of glacial melt in drought conditions. Technically, operating and maintaining the network required increasingly refined procedures, particularly to ensure consistent rating curves that relate water level to discharge. In high-altitude basins, channel morphology can shift following flood events or reservoir releases, requiring the use of different rating curves for different periods. At some stations, such as Braulio Valle, channel geometry varies seasonally, making it nearly impossible to define a stable rating curve. In these cases, the measured values are more indicative than strictly quantitative, and continuous in-situ monitoring is essential.

At regulated sites, flow variability is more pronounced due to artificial upstream control. This is particularly evident at finer time scales (daily or hourly), where sudden discharge changes reflect reservoir operations. Such dynamics must be interpreted on a case-by-case basis by field operators. One example is the Frodolfo stream at Santa Caterina (Forni Valle station), where it is recommended to install a radar sensor to avoid damage caused by sediment-laden floods. This site exemplifies the challenges and importance of improving sensor resilience in extreme mountain environments.

Table 2. Data availability by month (i.e. total number of days with reliable data in each month) from 2010 to 2024.

| | Forni | | | | | Gavia | | Braulio | | | Zebrù |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rosole | Cedec | Monte | Valle | Alpe | Monte | Valle | Stelvio | Monte | Valle | Zebrù |
| Jan | 31 | 198 | | 2 | 76 | 39 | | 62 | 176 | | 39 |
| Feb | 29 | 179 | | 4 | 73 | 29 | | 72 | 134 | | 43 |
| Mar | 31 | 211 | | 2 | 64 | 31 | | 78 | 126 | | 59 |
| Apr | 30 | 210 | | 32 | 60 | 30 | | 78 | 120 | | 60 |
| May | 31 | 209 | 4 | 48 | 67 | 36 | 4 | 62 | 121 | 9 | 61 |
| Jun | 80 | 170 | 65 | 82 | 84 | 69 | 30 | 60 | 101 | 30 | 84 |
| Jul | 210 | 208 | 120 | 159 | 174 | 131 | 53 | 128 | 110 | 54 | 107 |
| Aug | 242 | 217 | 100 | 199 | 217 | 155 | 62 | 155 | 93 | 62 | 145 |
| Sep | 214 | 225 | 53 | 158 | 225 | 129 | 60 | 150 | 123 | 60 | 149 |
| Oct | 135 | 239 | 34 | 102 | 187 | 122 | 48 | 128 | 155 | 47 | 93 |
| Nov | 53 | 187 | | 11 | 56 | 75 | 4 | 32 | 143 | | 30 |
| Dec | 31 | 157 | | 8 | 45 | 54 | | 31 | 94 | | 33 |
| TOT | 1117 | 2410 | 376 | 807 | 1328 | 900 | | 1036 | 1496 | | 903 |

Table 3. Data availability by year (total number of days with reliable data per year per station).

| | Forni | | | | | Gavia | | Braulio | | | Zebrù |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rosole | Cedec | Monte | Valle | Alpe | Monte | Valle | Stelvio | Monte | Valle | Zebrù |
| 2010 | | 105 | | 48 | 38 | | | | | | |
| 2011 | 195 | 359 | 65 | 183 | 41 | 193 | | 90 | 163 | | |
| 2012 | 328 | 321 | | 115 | | 328 | | 191 | | | |
| 2013 | | 363 | 78 | 28 | 198 | 203 | 154 | 292 | 173 | 149 | |
| 2014 | | 301 | | | 301 | 119 | 103 | | 331 | 113 | |
| 2015 | 124 | | 78 | 14 | 131 | | | | 109 | | |
| 2016 | 109 | | 30 | 108 | 101 | | | | 52 | | 71 |
| 2017 | 97 | | | 100 | 99 | 57 | | | 119 | | 82 |
| 2018 | 140 | 1 | 125 | 140 | | | | | 209 | | 141 |
| 2019 | | 105 | | | 104 | | | 99 | | | 98 |
| 2020 | | 1 | | | | | | | 142 | | |
| 2021 | | 165 | | 71 | 165 | | | 63 | | | 7 |
| 2022 | 72 | 180 | | | 150 | | | | 198 | | 319 |
| 2023 | 52 | 365 | | | | | | 182 | | | 185 |
| 2024 | | 144 | | | | | | 119 | | | |
| TOT | 1117 | 2410 | 376 | 807 | 1328 | 900 | | 1036 | 1496 | | 903 |

*Modelled discharge in Stelvio area*

Discharge was modelled using the Poli-Hydro model for each station of the IdroStelvio network from 1990 to 2025, with the exception of Braulio Valle and Gavia Valle, where the lack of consistent discharge measurements did not allow a calibration of the model. Figure 4-7 show average seasonal discharge and its components, e.g., snow and ice melt at the stations.

Figure 8 shows for the same subset of stations snow and ice melt contribution and total discharge vs. variables of interest, e.g. altitude for snow melt contribution, glacier covered area for ice melt contribution, and water catchment area for total discharge. Our results align well with the literature (Aili *et al.*, 2019; Stucchi *et al.*, 2019), with slightly higher glacier contributions possibly due to local conditions (e.g., glacier elevation and exposure).

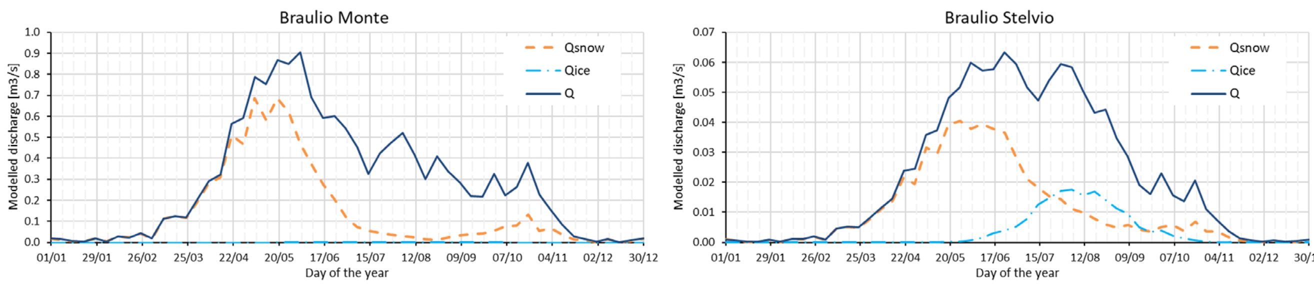


Figure 4 - Average simulated outflows and contributions at hydrometric stations in Braulio Valley for 1990-2023 (Stucchi, 2023).

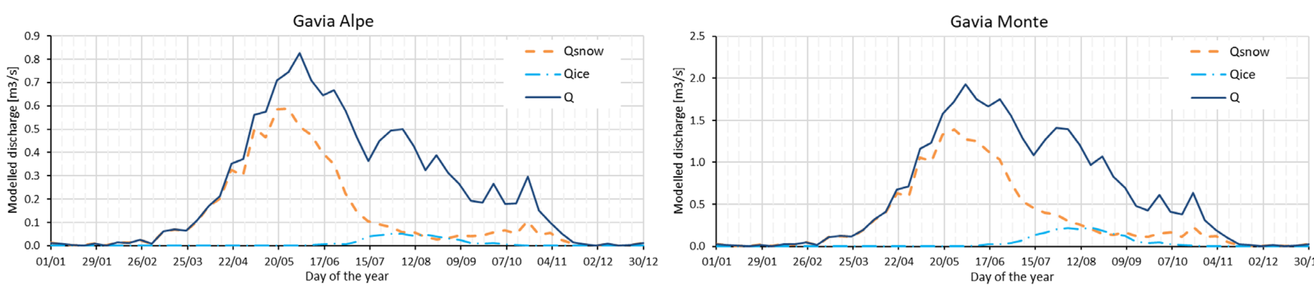


Figure 5 - Average simulated outflows and contributions at hydrometric stations in Gavia Valley for 1990-2023 (Stucchi, 2023).

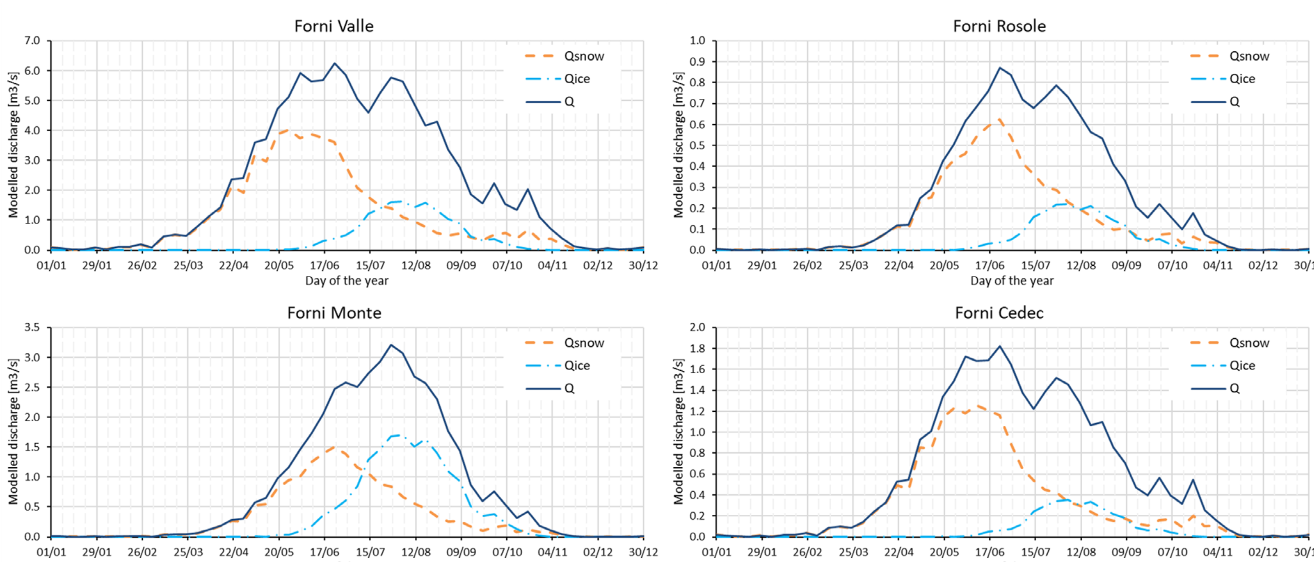


Figure 6 - Average simulated outflows and contributions at hydrometric stations in Forni Valley for 1990-2023 (Stucchi, 2023).

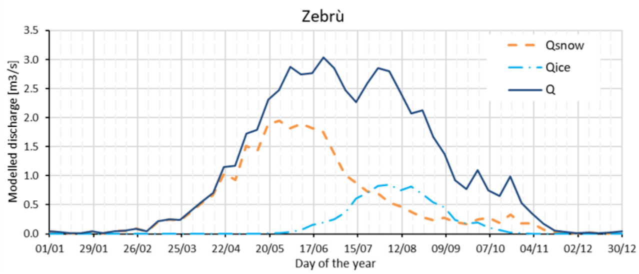


Figure 7 - Average simulated outflows and contributions at hydrometric stations in Zebrù Valley for 1990-2023 (Stucchi, 2023).

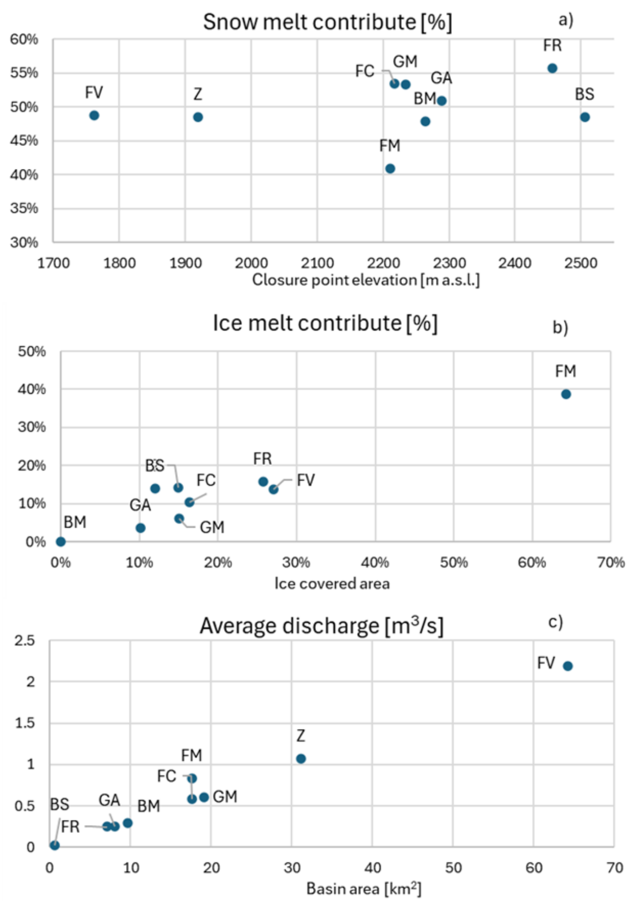


Figure 8 - a) Snow melt contribution to discharge vs elevation of closure point of the watershed, b) ice melt contribution to discharge vs ice covered area [%], c) average discharge vs. basin area. Z stands for Zebrù station, FM for Forni Monte, FC for Forni Cedec, FR for Forni Rosole, FV for Forni Valle, GA for Gavia Alpe, GM for Gavia Monte, BM for Braulio Monte, BS for Braulio Stelvio.

## DISCUSSION

### *Outputs of monitoring and hydrological model*

Discharge data extrapolated by water level measurement and rating curve provide useful information regarding the phases of snow and ice melting. They still cannot be considered for a detailed mass balance of water resources of upstream basins. The change in sensibility of the cell piezometer, the processes of sedimentation and erosion, the uncertainty in discharge measurements, make the extrapolated values of discharge too uncertain. However, relative changes of water level allow us to appreciate seasonal variation of discharge given by snow and ice contribution; therefore, they are a useful tool to calibrate snow and ice melt parameters for hydrological modelling. A properly calibrated hydrological model is a powerful tool to provide a consistent assessment of discharge and its components. In Figure 8 it is shown how seasonal water resources change according to basin size, altitude, and presence of glaciers.

### *The IdroStelvio network: limitations, potentialities and possible integrations.*

The IdroStelvio project constitutes a robust, long-term effort in high-altitude hydrological monitoring, carried out through a consolidated partnership between the Stelvio National Park and two major academic institutions. Over 15 years of continuous operation, the network has generated one of the most extensive and temporally consistent datasets on snow- and ice-fed streamflow available in the Italian Alps. This work has significantly contributed to advancing the empirical understanding of alpine hydrological regimes and has informed the development and calibration of glacio-hydrological models suited to cold and glacierized catchments.

Despite operating under severe environmental constraints – characterized by freezing temperatures, debris transport, variable channel morphology, and logistical inaccessibility – the network has maintained substantial data continuity. This has been achieved through adaptive management strategies, including the progressive integration of non-contact radar sensors, periodic recalibration of rating curves, and the implementation of semi-automated data validation protocols. These aspects underline the operational maturity of the IdroStelvio system and its potential as a reference framework for analogous monitoring efforts in other mountain regions.

IdroStelvio is one of the few hydrological monitoring networks at high altitude, with very few precedents worldwide, represented by the Chilean Andes (Masiokas *et al.*, 2019) and the Himalayas (Gautam and Acharya, 2012; Rautela *et al.*, 2022). The maintenance of a network system in harsh environment requires constant intervention from the operators, which is made possible thanks to the endorsement from the local institution, providing not only financial support, but also authorizations and logistic support for the maintenance operations.

The collected dataset confirms and expands upon previous findings in glacio-hydrology. In particular, it reinforces the critical influence of temperature on discharge regimes in glacierized catchments (e.g. Aili *et al.*, 2019), where peak discharges are recorded during high summer, in contrast to non-glacierized Alpine catchments where peaks occur during spring and early summer. This is due to the different sources of melting water: when snow depletion is completed, discharge in non-glacierized basins starts to decrease, while it eventually continues to rise if melting water from glaciers is available. The collected dataset also highlights the complexity added by anthropogenic regulation, which alters natural flow patterns. These observations have direct implications for model development, scenario analysis, and water resource planning under changing climate conditions.

Scientifically, the long-term dataset has enabled assessments of cryospheric contributions to runoff, allowed for robust model calibration, and offered insights into the role of glacial melt as a buffer during extreme drought conditions. Educationally, the network has proven instrumental in training a new generation of hydrologists through M.Sc. and PhD theses.

Looking ahead, potential enhancements to the network may include strategic rationalization of the station layout, the integration of sensor measuring suspended sediment, water temperature and chemical parameters such as pH, conductivity, $O_2$ content, and the implementation of telemetry-based real-time monitoring for early warning purposes. The network's data can be further leveraged for the analysis of ecological flows, low-flow forecasting, and seasonal water availability assessments, especially when coupled with meteorological forecasting tools.

In this context, collaboration with stakeholders – particularly the hydropower sector – may play a decisive role in sustaining and expanding the network's capabilities. Encouraging such partnerships would enhance not only data continuity but also the relevance of IdroStelvio in operational decision-making.

*Practical guidelines for monitoring snow-ice fed mountain streams in high-altitude environments*

Based on the 15-year experience of the IdroStelvio network, we propose a set of practical guidelines for the design, implementation, and maintenance of hydrometric monitoring systems in glacierized alpine catchments:

a) Site selection criteria

Monitoring stations should be located in representative catchments with varying degrees of glacier influence, ensuring coverage of different altitudinal belts and hydrological regimes, possibly excluding downstream water withdrawal. Whenever possible, stations should be anchored to stable infrastructures (e.g., bridges or large boulders) to enhance durability and accessibility.

b) Choice of the sensor and installation

Piezometric sensors are the most affordable, and the least energy consuming sensors. They provide accurate measurements in shallow, low-turbulence streams, and they can be placed everywhere there is a rock or a man-made structure to keep them stable during high flow. To mitigate the risk of damage from direct impact with debris, the sensor must be enclosed within a protective housing (e.g. rubber tubing), and the assembly must be oriented to face downstream. However, their accuracy decreases with time, and they are affected by low temperatures. Radar sensors, in contrast, provide more accurate measurements of their distance to the water surface. To translate these values into an absolute water level, it is necessary to establish the position of the bedrock, which can be approximated with the maximum value read by the instrument, corresponding to the minimum water level. Radar sensors are the optimal choice where a stable elevated structure (e.g. a bridge) is available and where sufficient solar insulation can be guaranteed for continuous battery operation. Solar panels must be positioned carefully in order to minimize snow accumulation and ensure maximum insulation. Furthermore, it is also suggested to place the sensors in a covert place, to reduce the visual impact and to reduce the risk of vandalism.

c) Discharge measurement and flow rate curve

Direct measurements of discharge can be performed using a current meter or a salt tracer. Current meter measurements are more accurate, but they are time consuming and raise safety concerns if the water level is too high. If the water level is lower than the current meter dimension, or other issues make it impossible to use it properly, it is suggested to use a salt tracer, i.e. a conductometer. It can provide consistent results if the stream is not too large, and if air bubbles are not present in water. In case of high turbulence, both methods are less efficient, making the flow rate curve less reliable for high water levels.

d) Maintenance and calibration protocols

Regular field inspections are required to verify sensor integrity, check the stability of river sections, recalibrate rating curves, and replace damaged components. Stage-discharge relationships should be updated annually and after major hydrological events. Winterization procedures must be adapted to site-specific conditions.

e) Data validation and management

Raw data should undergo semi-automated filtering based on temperature thresholds and physically plausible ranges, followed by visual inspection. Metadata on station status, maintenance logs, and environmental conditions should be systematically recorded to support data interpretation.

f) Network evolution and integration

Future upgrades may include telemetry systems for real-time data transmission, integration of sensors for water temperature, sediment load, and chemical parameters (e.g., pH, conductivity, dissolved oxygen), and coupling with meteorological forecasting tools for early warning applications.

These guidelines aim to support the replicability of high-altitude hydrological monitoring systems and foster the development of standardized protocols in glacio-hydrology.

*Originality of the IdroStelvio project*

While numerous studies have addressed the hydrology of glacierized catchments and the modeling of snow and ice melt contributions, few have proposed operational guidelines for the monitoring of snow-ice fed mountain streams in high-altitude environments. The IdroStelvio project fills this gap by offering a field-tested framework based on 15 years of continuous monitoring in the Italian Alps.

Recent works such as Müller *et al.* (2025) have explored the use of isotopic tracers to distinguish between snow and ice contributions to streamflow, suggesting methodological improvements for glacio-hydrological modeling. However, their focus remains on data interpretation rather than on the design and maintenance of monitoring networks.

A case study from the Teton Range (Tronstad *et al.*, 2019) presents long-term monitoring of alpine streams from various sources, including glaciers and snowfields. While informative, it does not offer structured guidelines or a replicable network model comparable to IdroStelvio.

In contrast, the present work combines empirical data, technical experience, and methodological synthesis to propose a set of practical recommendations for hydrological monitoring in glacierized regions. These guidelines are not intended as definitive standards but as a starting point for shared protocols that can be refined through collaboration with other networks and operators working under similar environmental constraints This operational focus makes IdroStelvio a unique contribution to the field, complementing existing modeling and remote sensing approaches with actionable field-based practices.

## CONCLUSION

The IdroStelvio project demonstrates how long-term, high-resolution monitoring in glacierized alpine environments can support both scientific research and adaptive water resource management. Over 15 years of continuous operation, the network has provided valuable insights into the hydrological behavior of snow- and ice-fed streams, contributing to the development of glacio-hydrological models and informing climate impact assessments.

Beyond its scientific outputs, the project has yielded a set of practical guidelines for the design, implementation, and maintenance of hydrometric networks in high-altitude catchments. These guidelines, grounded in field-tested procedures and adaptive strategies, aim to support the replicability of similar systems in other mountain regions.

However, these recommendations should not be considered definitive. Rather, they represent a first step toward the development of shared protocols in glacio-hydrology. Their refinement will benefit from future comparisons with other monitoring networks operating under similar environmental constraints. As more data, experiences, and technical solutions become available, these guidelines can evolve into a more robust and widely applicable framework.

In this perspective, fostering collaboration among researchers, institutions, and stakeholders involved in high-altitude hydrological monitoring will be key to improving data quality, operational resilience, and the overall impact of such networks on science and policy

## AUTHORS CONTRIBUTION

D.B. and G.A.D. conceived and designed the monitoring network and the idea of this work; D.B., L.S., D.F., M.A., C.D.A., R.S.A., B.B, D.B., C.C., P.D., L.F., S.M., L.S., G.T., G.P.V. and G.A.D. helped in collecting discharge data and maintaining the stations of the IdroStelvio network; L.S. analysed the data; A.S. and D.F. assisted in the management of the network; L.P., on behalf of Stelvio National Park, contributed to the project through institutional representation and active support in the development of the IdroStelvio network; D.B., L.S., D.F., A.S. and G.A.D. wrote and reviewed the manuscript.

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## DATA AVAILABILITY

Data are available upon request to the corresponding author, pending authorization from Stelvio National Park, which owns the monitoring network

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