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Modelling Glacier Ice Avalanches for Infrastructure Risk Assessment in the Alps: Insights from the PNRR - Ecosistema dell'Innovazione "Nord Ovest Digitale e Sostenibile" Project

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Abstract

Climate change is driving significant cryospheric degradation in the European Alps, potentially increasing the frequency of glacial hazards such as ice avalanches. This study presents an integrated, reproducible workflow to assess the vulnerability of hydroelectric infrastructure in the Aosta Valley, Italy. The methodology combines a statistical analysis of historical European events with stochastic numerical modelling. A robust relationship between collapse volume and the angle of reach was derived using bootstrap regression. Glacier release points were identified by intersecting flowlines with glacier fronts, applying a densification strategy for complex ice bodies. Potential runout scenarios were simulated using the r.randomwalk model on a normalized 24 m Digital Elevation Model (DEM), comparing datasets from 2000 and 2008 to evaluate sensitivity to glacial retreat. Results highlight localized criticalities, particularly in the Valpelline sector, where collapses from the Luseney and Solatset glaciers could directly impact intake structures and reservoirs. In Valtournenche, simulations identify scenarios that approach the Perrères power plant. Despite these specific risks, the regional energy network demonstrates high overall resilience. This approach provides a valuable tool for prioritizing monitoring and mitigation strategies in high-mountain energy planning.

1. Introduction

Current climate change scenarios are driving profound global environmental transformations, with particularly critical repercussions in high-altitude mountain regions. In these environments, elevation-dependent warming amplifies temperature increases, accelerating the degradation of the cryosphere (Gobiet et al., 2014). This process manifests through glacier melting and a consequent increase in the frequency and intensity of glacial hazards, including ice avalanches (Bondesan and Francese, 2023). These phenomena represent a growing threat not only to anthropized areas but also to strategic infrastructure located at high altitudes. In this context, the main objective of this work, developed within the framework of the NODES project, is to define and validate a reproducible procedure for assessing the risk of interference between glacial collapse processes and hydroelectric infrastructure. The selected pilot area is the Aosta Valley, a region characterized by a high density of glaciers and a widespread presence of facilities managed by Compagnia Valdostana delle Acque (CVA). Through the integration of historical data, statistical analysis, and spatial numerical modelling, this research aims to provide new tools for risk management and resilient infrastructure planning in the Alpine environment.

2. Study area and input data

2.1 Study area

The investigation focuses on the Aosta Valley (Figure 1), situated in the north-western sector of Italy. This region constitutes the most heavily glaciated area in Italy, hosting over a hundred glacial bodies distributed along the main Alpine massifs. Such a geographical context offers ideal conditions for the application and validation of the proposed methodology, due to the significant morphological diversity characterizing the local glaciers. Indeed, the regional glaciological landscape ranges from small, highly channelized bodies to complex glaciers with broad fronts and intricate flow dynamics.A further determining factor in the site selection is the presence of an extensive and dense hydroelectric network, with infrastructure located even at high elevations. This specific anthropogenic setting makes the Aosta Valley a prime laboratory for studying potential interferences between glacial processes and strategic engineering structures. Finally, the availability of glaciological, topographical, and infrastructural datasets provided the necessary foundation to implement and robustly test the entire modelling workflow developed.

2.2 Data

The analysis was developed by integrating two sets of glaciological and topographical data obtained from cartographic databases and previous studies, with the aim of comparing results derived from global-scale datasets with those obtained

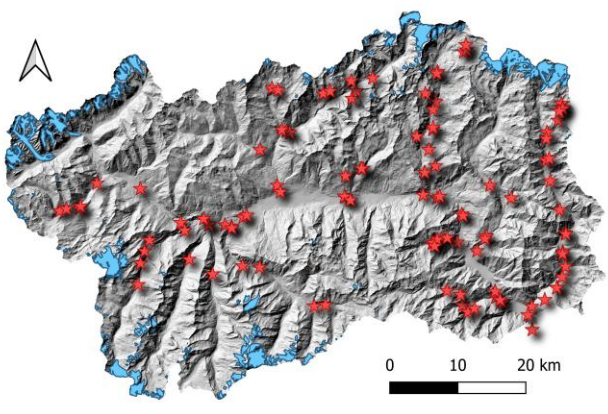

Figure 1: Map of the distribution of glacial areas (blue polygons) and CVA infrastructure (red stars) in the Aosta Valley.

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from high-resolution regional data. The elevation component was reconstructed using the 2000 Shuttle Radar Topography Mission (SRTM) digital elevation model (NASA, 2013) for broader-scale simulations and the 2008 regional DEM, available through the Autonomous Region of Aosta Valley geoportal (https://geoportale.regione.vda.it). Regarding glacial characterization, perimeters were derived from both the Randolph Glacier Inventory (RGI Consortiun, 2023), a subset of the Global Land Ice Measurements from Space (GLIMS) database referring to the year 2000 and the 2005 regional glacier inventory, also available from the geoportal. Similarly, for the estimation of glacial volumes, thickness datasets published by Farinotti et al. (2019) were used, alongside data produced at the regional level by the Regional Environmental Agency. Glacial flowlines were also obtained from the Randolph Glacier Inventory and subsequently harmonized with the regional perimeters. Finally, the location of hydroelectric infrastructure was provided in shapefile format directly by CVA. For convenience, the two data sets have been named 2000 database and 2008 database.

2.3 r.randomwalk

r.randomwalk is a versatile, open-source tool designed for both the forward and back-analysis of mass movement propagation. The software routes hypothetical mass points from defined release pixels across a DEM until specific termination criteria are met. Lateral flow dispersion is simulated using either Monte Carlo techniques, specifically random walks (Pearson, 1905), or multiple flow direction algorithms (Horton et al., 2013). This random walk approach facilitates the realistic simulation of mass movement trajectories, such as debris flows, over elevation maps. By permitting movement directions that deviate from the line of steepest descent, this method achieves a realistic flow spread, preventing the artifact of excessively linear and implausible propagation often associated with deterministic routing. Nevertheless, the routing process remains governed by physical factors, including local slope gradients and the flow's inertial tendency to maintain its prior direction. Each random walk iteration continues until the flow path exits the study area or a user-defined stopping condition is satisfied. These criteria are critical for delineating the potential impact area and typically involve threshold values for the angle of reach (the average slope of the path) or specific horizontal and vertical travel distances, which may be dynamically linked to the mobilized volume (Mergili et al., 2015).

3. Methodology

3.1 General workflow

This study proposes an integrated approach for ice avalanche risk assessment, combining statistical analysis of a historical event database with stochastic numerical modelling using the r.randomwalk software. The operational workflow is structured into the following main phases:

1. Database construction and statistical analysis: collection of data on historical ice avalanches, calculation of the angle of reach, and definition of representative volume classes derived from bootstrap regression analysis.
2. Glacier characterization: estimation of glacier volumes via zonal statistics on raster data and classification of glaciers according to the defined volume classes.
3. Definition of release points: identification of release points through the intersection of glacier outlines and processed flowlines, applying a point densification strategy along glacier fronts.
4. Numerical simulations: execution of the r.randomwalk model utilizing the identified release points, the DEM, and friction parameters derived from the statistical analysis.
5. Impact assessment: generation of Impact Frequency (IF) maps and spatial analysis of potential interferences with hydroelectric infrastructure.

3.2 Database construction and statistical analysis

The initial phase involved the creation of a comprehensive ice avalanche database, compiling both historical records and recent events (Alean, 1984; Chiarle et al., 2022). Data selection was strictly limited to European events. Asian events were excluded because they often reach magnitudes in the order of millions of cubic meters, exhibiting characteristics not comparable to the Alpine context. Furthermore, smaller events in such regions are poorly documented due to the limited interaction with anthropogenic infrastructure. For each documented event, the collapse volume, runout distance (L), and elevation drop (H) were parameterized. Based on these data, the tangent of the angle of reach (ω) was calculated as the ratio H/L, following the empirical relationships proposed by Alean (1985). Subsequently, the tangent of the angle was correlated with the logarithm of the volume on a scatter plot (Figure 2). To derive a robust relationship from the scatter of real-world cases, a bootstrap analysis was performed. This statistical resampling technique estimates the sampling distribution of an estimator (in this instance, the regression line) by repeatedly extracting random samples with replacement from the original dataset. This process enabled the determination of the mean regression line for the data cloud. To quantify the uncertainty associated with the model, two fundamental statistical intervals were calculated: the confidence interval, that represents the uncertainty related to the estimation of the regression line itself, and the prediction interval, that accounts for the intrinsic uncertainty of natural variability. Based on this analysis, five representative volume thresholds were defined: 50,000 m^3, 200,000 m^3, 500,000 m^3, 1,000,000 m^3, and 6,000,000 m^3. The lower limit corresponds to the volume below which collapse events do not produce significant impacts, as they typically fail to reach the valley floor under summer conditions (i.e., without snow cover) according to the database. Conversely, the upper limit represents the historical maximum known for an ice avalanche in the Alpine environment (Faillettaz et al., 2011). For each volume class, five corresponding angles of reach values were derived. These were determined by the intersection of the vertical line corresponding to the volume with the mean regression line, as well as with the upper and lower limits of the calculated confidence and prediction intervals.

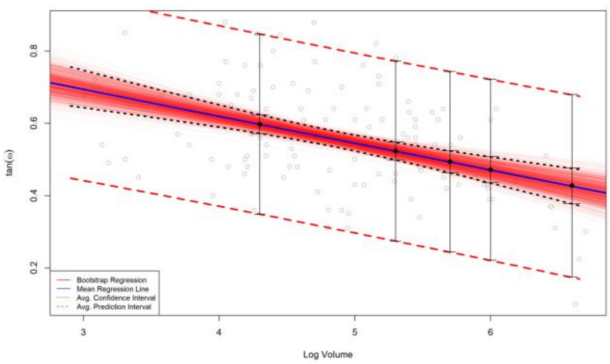

Figure 2: Bootstrap regression scatterplot between the collapse volume and the tangent of the angle of reach for ice avalanches.

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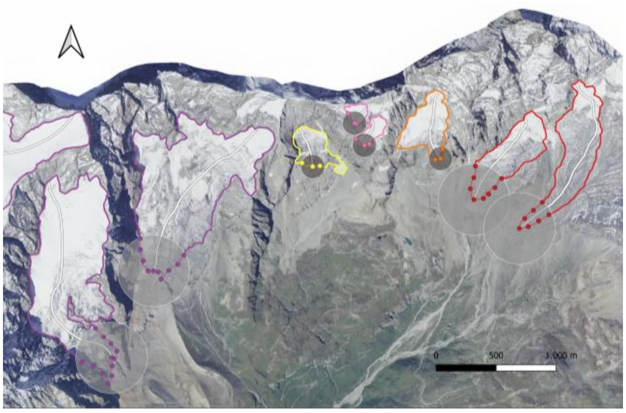

Figure 3: Map of a few glaciers in Valtournenche and their release points.

3.3 Glacier characterization and definition of release points

The simulation of collapse events necessitates the precise definition of release points, relying on the assumption that failures predominantly occur at the glacier front (Alean, 1985). The entire geospatial analysis was conducted within the QGIS environment, an open-source software dedicated to spatial data analysis and mapping. Glacier volumes were estimated by integrating the glacier outline inventory with ice thickness raster data. By employing the Zonal Statistics tool, the sum of thickness values was calculated for each polygon in the perimeter layer. This sum, multiplied by the pixel area (25 m x 25 m), provided an estimate of the individual glacier volume, allowing for its subsequent assignment to the previously defined volumetric classes. The geometric localization of release points was achieved by processing glacial flowlines, theoretical trajectories of ice mass movement calculated orthogonal to surface contours along lines of steepest descent. Starting from the raw shapefile, the dataset underwent a rigorous refinement process: first, flowlines external to the Aosta Valley glaciers of interest were excluded; second, the geometries were modified to ensure lines intersected polygon boundaries exclusively at the glacier front, removing any upstream or internal intersections; and third, lines failing to strictly follow drainage or steepest descent paths were manually rectified using the slope raster for validation. The intersection between these corrected flowlines and glacier perimeters identified the primary release point. However, preliminary testing indicated that a single point is sufficient only for small or highly channelized glaciers. For extensive and morphologically complex glaciers characterized by differentiated flow zones, a single release point is neither representative nor capable of accounting for the uncertainty inherent in identifying the exact detachment location. Consequently, a point densification strategy was adopted: starting from the primary point, additional points were generated along the glacier terminus at 100 m intervals. A selection buffer, set at a 300 m radius for glaciers with volumes > 500,000 m^3 and 100 meters for smaller volumes, was applied to retain only relevant locations, yielding a minimum of three release points for smaller glaciers and at least seven for larger ones (Figure 3). To estimate the potential magnitude of detachment events, these release points were classified according to the same five volumetric categories used for glacier classification. This categorization allows for the assessment of the potentially mobilizable ice volume associated with each specific release point.

3.4 Numerical simulation and impact assessment

The processed input data, specifically release points and friction angles, were utilized in the r.randomwalk model to simulate avalanche propagation. To ensure result robustness, a sensitivity analysis was conducted by performing multiple simulations with varying DEM resolutions and key flow parameters, thereby assessing the model's response to different input configurations. Following preliminary testing, the final simulations were configured with a logarithmic scale of iterations (10^5) and a minimum avalanche runout distance of 80 m. The latter parameter ensured the simulated mass gained sufficient inertia to overcome minor topographic depressions immediately downstream of release points, which might otherwise have caused premature flow termination. To ensure comparability across simulation runs and manage the heterogeneity of topographic datasets, a constant DEM resolution of 24 m was maintained. This resolution was selected after evaluating its influence on the lateral spread of impact areas and the model's ability to adapt to terrain roughness, effectively minimizing the number of confounding variables. The primary output of the simulations consists of Impact Frequency maps. This metric provides a positive, dimensionless value quantifying the number of stochastic random walks traversing a specific pixel. It serves as a proxy for the spatial probability of transit and delineates the potential extent of the hazard zone. Finally, these hazard zones were intersected with the geolocated CVA hydroelectric infrastructure to calculate minimum distances from impact areas, thereby assessing the risk of interference.

4. Results

The primary objective of this project is to develop a procedure to simulate ice collapse phenomena and assess their potential interactions with energy infrastructure, with a specific focus on the hydroelectric systems managed by Compagnia Valdostana delle Acque. This specific focus stems from the strategic role energy infrastructure plays in contemporary society and its frequent location in high-altitude environments, where it may be exposed to gravitational hazards such as ice avalanches. While the initial analysis targeted hydroelectric facilities, the proposed methodology is applicable to the entire regional territory, allowing for the identification and assessment of potential interferences between glaciers and critical infrastructure. This encompasses both anthropized areas, such as roads, residential buildings, and structures, and natural environments used for recreation, such as hiking trails or ski resorts, thereby providing a useful framework to guide risk management and mitigation strategies. The simulations conducted to date confirm the efficacy of the proposed methodology in reproducing the main dynamics associated with glacial collapses. The strategy of analysing multiple release points, identified along the

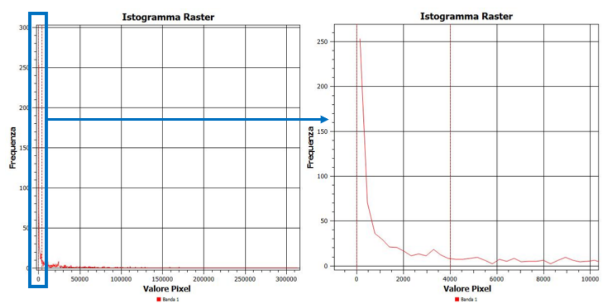

Figure 4: Frequency histogram of the Impact Frequency rasters.

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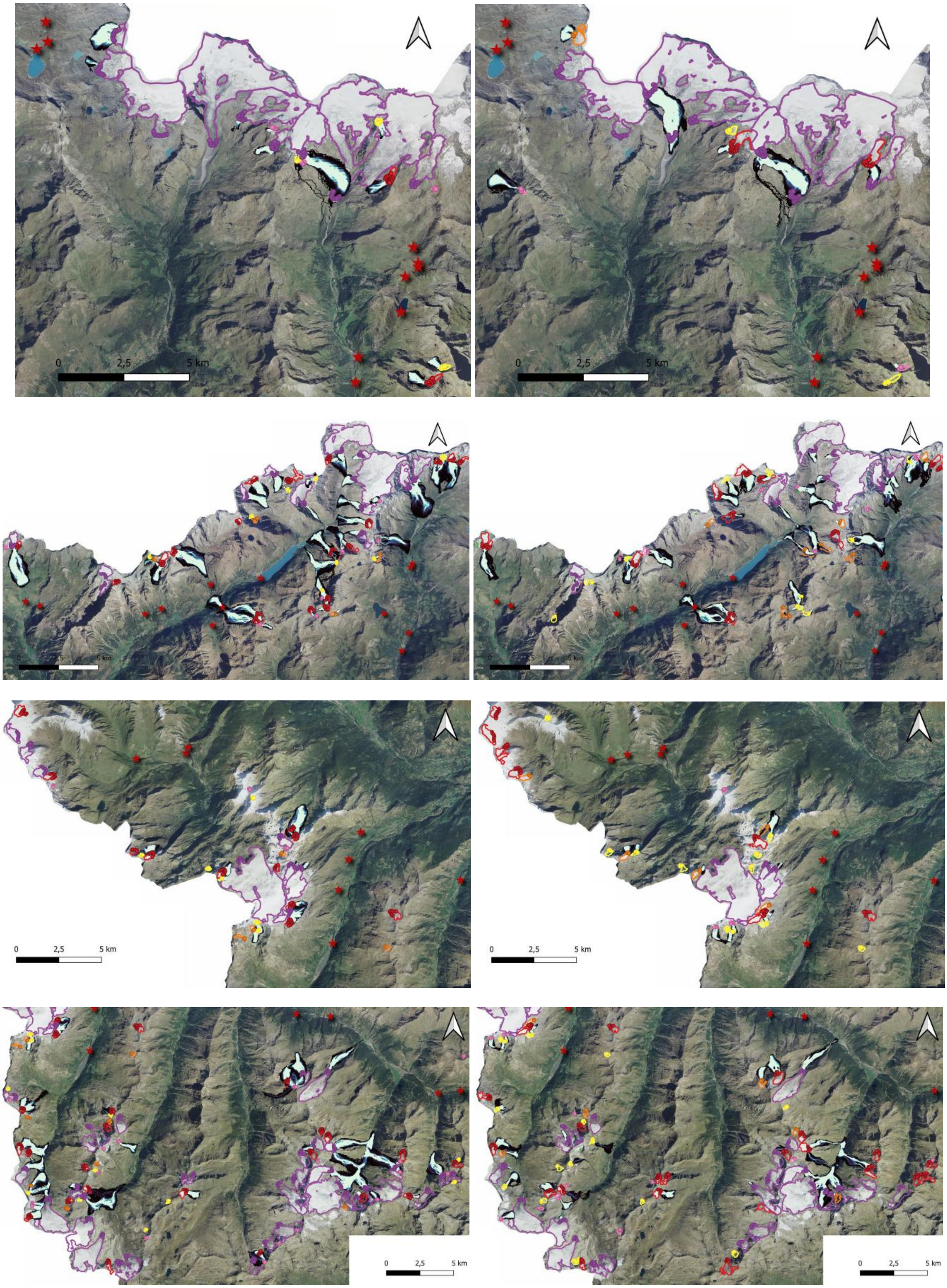

Figure 5: Maps of impact areas and Impact Frequency rasters for the 2000 (left column) and 2008 (right column) data sets for the areas of, from top to bottom: Monte Rosa, Valpelline and Valtournenche, Rutor massif and Gran Paradiso National Park.

intersections between flowlines and glacier perimeters, proved particularly advantageous. This approach allows for a more realistic representation of the uncertainty regarding detachment localization and generates a broader and more plausible set of scenarios. Impact Frequency maps generated via r.randomwalk simulations exhibit coherent spatial patterns in potentially hazardous areas, highlighting specific valleys and slopes with higher exposure to ice avalanche trajectories. An analysis of the frequency distribution of the Impact Frequency rasters reveals that the vast majority of potentially affected pixels exhibit relatively low IF values (Figure 4). The global view (spanning values up to ~300,000) shows a flat distribution for high values, while the detailed view (zoomed on the 0–10,000 range) highlights a sharp, asymptotic decay in frequency as pixel values increase. This statistical behaviour indicates that while the simulated hazard zone covers a broad area, the highest probability of transit is spatially concentrated along the central axes of the flow paths, where the random walks tend to converge. In a few scenarios, simulated events approach within a few hundred meters of hydroelectric infrastructure, underscoring the importance of systematically including these processes in regional-scale risk assessments (Figure 5).

Simulations conducted in the Monte Rosa Massif did not reveal significant criticalities or evidence of potential interferences between glacial collapses and hydroelectric infrastructure. A more critical situation emerges in the Valpelline sector, where both simulation sets indicate that collapses from the Luseney glacier with volumes ranging between 200,000 m^3 and 1,000,000 m^3 would reach the subsidiary intake of T. Arbière. Conversely, smaller magnitude events of approximately 50,000 m^3 would approach the upstream intake without direct impact. The two simulation sets demonstrate good consistency in Impact Frequency values. Specifically, for 200,000 m^3 collapses, the IF is approximately 30,393 (2000 database) and 44,911 (2008 database); for 500,000 m^3 volumes, the IF increases to approximately 100,262 (2000 database) and 161,280 (2008 database); finally, for collapses in the order of 1,000,000 m^3, the IF reaches values of approximately 118,980 (2000 database) and 190,869 (2008 database). Furthermore, a high-magnitude event in the order of 1,000,000 m^3 originating from the Solatset glacier could partly involve the Places de Moulin basin, entailing the risk of obstructing the Buthier torrent; potential cascade effects on the reservoir could be further investigated in the future. In the Valtournenche area, modelling results show that an ice avalanche originating from the Mont Blanc du Creton glacier would terminate approximately 600 meters from the Perrères hydroelectric power plant and the nearby Perrères dam, assuming a collapse volume of 50,000 m^3 using the 2000 dataset. Simulations based on the 2008 dataset relating to a 200,000 m^3 collapse, show that the ice avalanche would stop less than 400 meters from the power plant and the Perrères dam. Finally, regarding the Rutor massif, no significant interferences were recorded between ice avalanches and CVA energy infrastructure. Similarly, the Gran Paradiso National Park area shows no significant direct interference between ice avalanches and CVA energy infrastructure. Preliminary findings indicate that integrating statistical, empirical, and physically-based modeling approaches yields consistent and significant results. The methodology proved effective in identifying potential interferences between glacial collapses and critical energy infrastructure, offering a solid foundation for future extensions to other asset types and for applications at both regional and broader scales.

5. Discussion and validation

The comparison between simulations based on the 2000 and 2008 databases reveals a general consistency in results, despite some geomorphological and modelling disparities. In several instances, simulations based on the 2000 dataset exhibit longer ice avalanche runout distances compared to those derived from 2008 data. This behavior is primarily attributable to the 2000 glacier outlines that generally extend further down-valley than their 2008 counterparts, reflecting the marked glacial retreat and mass loss that characterized the interval between the two datasets. A second element contributing to simulation discrepancies involves the differing segmentation of glacial bodies within the two inventories. In certain cases, glacial units listed as separate in 2008 appear merged in the 2000 dataset, or vice versa (e.g., Trelatete Orientale and Trelatete Nord-Est, Planpincieux and Grandes Jorasses, Colle del Gigante and Mont Fréty, and Brenva). These variations in segmentation lead to differences in both input volumes and modelled release points, generating collapse scenarios that are not always directly comparable. Furthermore, when using multiple release points, the r.randomwalk model aggregates the Impact Frequency values from different simulated paths converging on a single pixel, thereby amplifying the spatial variability of the impact zone. A critical finding of the analysis concerns the influence of DEM resolution on simulated propagation. Although the 2008 database includes a native high-resolution DEM (2 m), and a downsampled 6 m DEM was also tested, propagation in both instances proved to be excessively constrained by local topographic irregularities, such as depressions or minor morphological traps. Conversely, the use of a 24 m DEM, matching the resolution adopted for the 2000 dataset, proved more suitable for simulation purposes. The increased generalization of the topographic model mitigates the effect of local artifacts, allowing the simulated flow to more accurately follow the valley's main drainage lines. Similar considerations apply to release points: at excessively high resolutions, unfavourable micro-slopes can prevent simulation initiation, an issue significantly mitigated by using the 24 m resolution.

Simulations conducted on both datasets were validated against documented and mapped ice avalanche events within the region (Figure 6). The Frébouze glacier case study is particularly representative: models based on both the 2000 and 2008 datasets adequately reproduce the runout extent of the 2002 event (Deline et al., 2002). As expected, the simulation exhibits a wider lateral spread compared to the observed event. This characteristic is attributable to the use of multiple release points and the summation mechanism of random paths within the IF maps, which tends to generate more diffuse probability zones. A further validation case using documented events is provided by the Planpincieux glacier. Here too, simulations relative to the 2000 and 2008 datasets show good correspondence between modelled collapses and the area actually affected by the 2017 event (Giordan et al., 2020). Finally, for the Lex Blanche glacier, simulations consistently reproduce the 2004 event, which is documented in the regional registry of subsidence events (https://catastodissesti.partout.it), confirming the methodology's reliability in reconstructing historically documented glacial collapses.

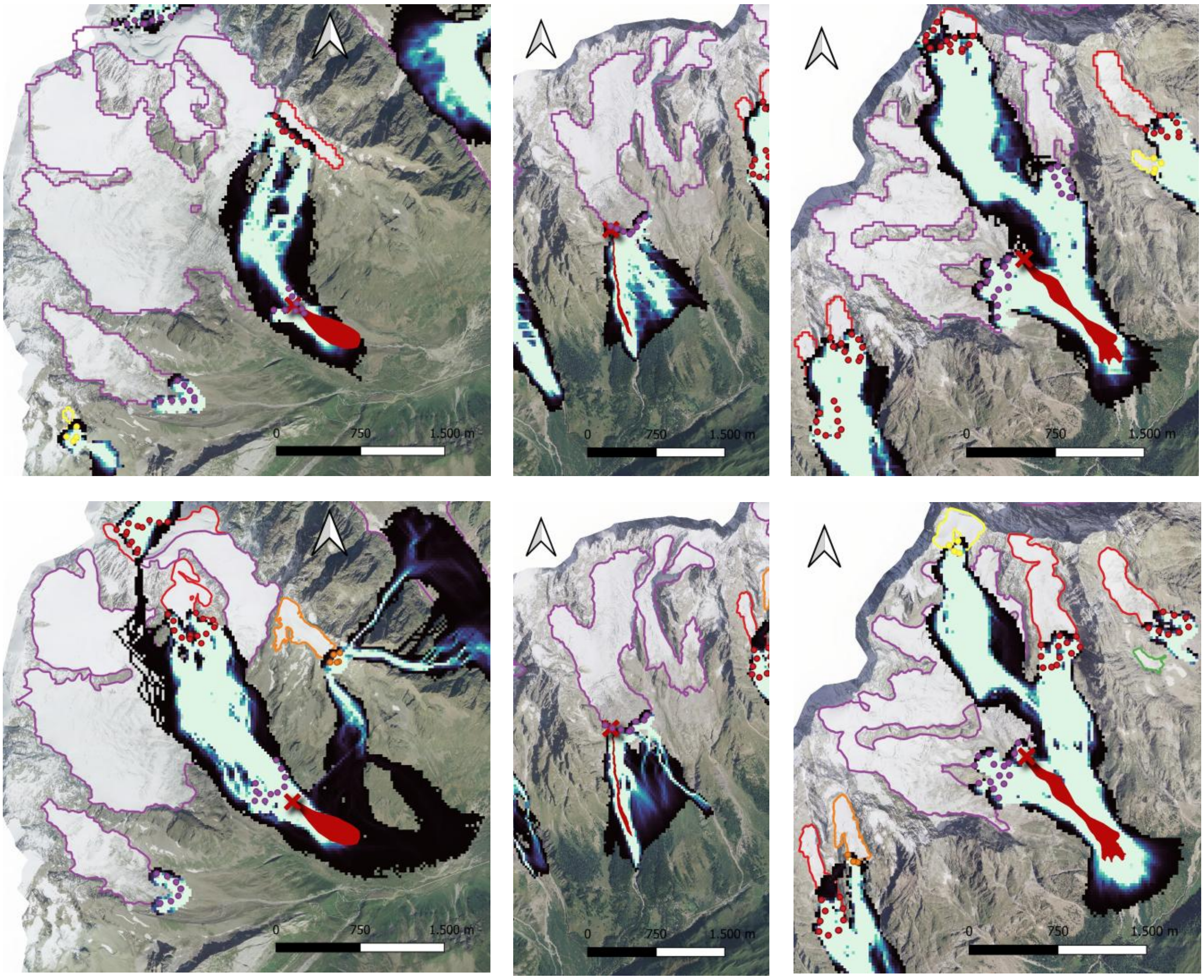

Figure 6: Validation of simulations from the 2000 (first row) and 2008 (second row) databases by comparing them with historical ice avalanche events (red area) from several glaciers in the Aosta Valley, from left to right: collapse of Frebouze (2002), Planpincieux (2017) and Lex Blanche (2004).

6. Conclusions

This study represents a foundational step in assessing the potential impacts of glacial destabilization within the Aosta Valley territory. Preliminary results indicate that the effects on the CVA energy distribution network infrastructure are generally limited and highly localized, confirming the system's overall resilience to the considered glacial collapse events. In instances where simulated deposition areas lie in close proximity to energy infrastructure, it would be advisable to plan targeted interventions to update available data, including: glacier outlines, topographic models, ice thickness, and geophysical surveys. Such updates would enable the refinement of risk assessments and support the design of potential mitigation measures. Furthermore, for sites of particular strategic interest, additional simulations could be conducted using more advanced numerical models (e.g., r.avaflow) to obtain more detailed estimates of collapse propagation and runout distances. Beyond energy infrastructure, future analyses could also encompass other sensitive territorial elements, such as roads, buildings, and critical infrastructure, to provide a more comprehensive risk assessment at the regional scale. Finally, it is crucial to consider potential cascading phenomena resulting from glacial collapses, such as the formation of ephemeral lakes and the associated risk of Glacial Lake Outburst Floods (GLOFs), which could generate significant indirect effects on the territory. The detailed study of such secondary processes lies beyond the scope of this project and may be the subject of future analysis. Integrating these aspects into planning frameworks will strengthen prevention and risk management strategies associated with gravitational hazards in high-mountain environments.

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