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Rapid landslide analysis in an Alpine watershed: a case study of the Rio Fenils (NW Italy)

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Abstract

This study, developed within the framework of the "Rapid landslide risk mitigation: design for sustainability criteria in mountain areas" (RaRiskD) – PRIN 2022 program (D.D. 104 - 02/02/2022 Ministerodell'Università e della Ricerca – CUP E53C24002910006), investigates rapid landslide processes affecting the Rio Fenils watershed, in the vicinity of the former Chaberton Military Road (Cesana Torinese, Western Alps, Italy). Repeated debris flow events have severely damaged the historical road, leading to its permanent closure to traffic. The research integrates geological, geomorphological, and historical analyses to evaluate the local susceptibility to rapid landslides using the DfPI methodology. A high-resolution digital terrain model was produced through UAV photogrammetry, providing the basis for detailed geomorphological interpretation and numerical simulations. Rainfall data from nearby monitoring stations were processed to identify critical precipitation thresholds responsible for triggering debris flow events. The HEC-RAS code was employed to simulate propagation scenarios under varying rainfall conditions and return periods. The outcomes highlight the dynamic behavior and destructive potential of these mass movements, stressing the need for improved hazard assessment and mitigation measures. The approach demonstrates how the integration of remote sensing, rainfall analysis, and numerical modeling can effectively support the design of protective structures and risk management strategies in alpine environments, particularly under the evolving impacts of climate change.

Keywords

Rapid landslides, Susceptibility, Mountain area, Risk management.

1 Introduction

Debris flows represent one of the most hazardous mass-wasting processes in alpine environments due to their high velocity, elevated sediment concentration, and strong impact forces (Jacob et al. 2024). These phenomena typically originate from the rapid mobilization of colluvial and glacial deposits under intense rainfall or accelerated snowmelt, often involving channelized transport along steep headwater catchments (de Haas et al. 2024). In the Western Alps, recent evidence suggests an increasing frequency and magnitude of such events, likely associated with climate-driven modifications of the cryosphere, including glacier retreat and permafrost degradation, which contribute to slope destabilization and enhanced sediment availability (Cantonati et al. 2025).

The Rio Fenils watershed, located in the upper Susa Valley (Cesana Torinese, Northwestern Italy), constitutes a representative alpine basin characterized by steep morphologies, abundant unconsolidated deposits, and active geomorphic dynamics. The basin is crossed by the former Chaberton Military Road, constructed in 1910 to access the highest fortification in Europe. Since 1987, vehicular access has been prohibited due to recurrent slope instabilities. A major debris-flow event on July 1, 2019, destroyed the ford across the Rio Inferno channel, resulting in the complete interruption of road continuity (CFVAS 2019).

The present study aims to provide a quantitative characterization of debris-flow processes within the basin and to support the design of mitigation and restoration measures for the affected infrastructure. The methodological framework integrates geological and geomorphological field surveys, analysis of historical events, hydrological assessment of triggering conditions, and geotechnical characterization of involved materials. A multiscale approach is adopted: at the basin scale, susceptibility mapping is performed through terrain analysis and morphometric indicators; at the slope and channel scale, detailed stability assessments and hydraulic simulations are conducted to evaluate flow propagation, impact pressures, and erosion potential. High-resolution digital terrain models derived from UAV-based photogrammetry and remote sensing are coupled with two-dimensional numerical modeling (HEC-RAS) to simulate debris-flow routing and to support the dimensioning of structural countermeasures.

2 Geological and Geomorphological Framework

The study area is located within the Penninic Domain and is more precisely referred to the Chaberton–Grand Hoche–Grand Argentier tectonostratigraphic unit. The bedrock succession is chiefly composed of Triassic dolostones overlain by Rhaetian–Cretaceous limestones. These competent yet intensely fractured lithologies give rise to steep rock slopes that constitute the primary source areas for detrital production. Rockfall processes continuously supply coarse debris, which accumulates at the foot of the slopes and represents the main sediment reservoir subsequently mobilized by debris flows (Fig. 1).

From a geomorphological standpoint, the Rio Fenils watershed exhibits a pronounced U-shaped cross profile inherited from Pleistocene glacial sculpting. Under present-day postglacial conditions, slope processes and fluvial dynamics dominate landscape evolution. Detailed geomorphological mapping shows that nearly 50% of the catchment is mantled by gravity-driven deposits, including active debris cones and alluvial fans. The Rio Fenils incises these unconsolidated sediments, locally generating steep erosional scarps and promoting their progressive reworking.

Documentary sources record recurrent debris-flow activity in the Chaberton–Rio Fenils–Rio Inferno sector between 1708 and 2019. Most events occurred during the summer months and were triggered by short-duration, high-intensity convective rainfall. The most significant episodes (1708, 1957, 1990, 1998, 1999, and, more recently, 2002, 2004, 2015, 2017, and 2019) produced channel instability, bank erosion, substantial sediment transport, and damage to infrastructure. The 1 July 2019 event was particularly severe, leading to the destruction of sections of the former Chaberton military road, which remains closed. The persistence of debris-flow activity attests to the high hydro-geo-morphological hazard characterizing the basin, as also highlighted in the susceptibility map of ARPA Piemonte,

which classifies the basin as highly susceptible and identifies the dominant lithology as ECM (Excellent Clay Marker) (Tiranti et al., 2008).

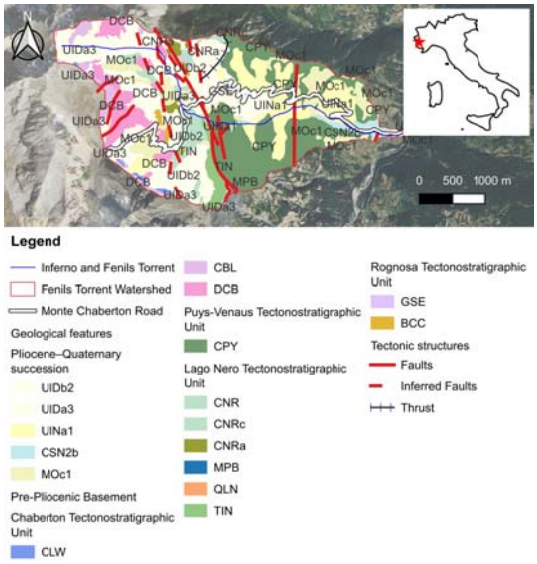


Fig. 1Geological sketch map of the Fenils Torrent watershed (modified from the Italian Geological Map at a scale of 1:25,000 – Sheet 171, Cesana). UIDb2: eluvial–colluvial deposits; UIDa3: debris deposits; UINa1: landslide deposits; CSN2b: debris-flow deposits; MOc1: undifferentiated till of the Mocenisio Supersystem; CLW: Les Arbours Complex – carbonate–schist complex; CBL: Cote Belle Limestones; DCB: Chaberton Dolomites; CPY: Puys Complex – calcschists; CNR: Lago Nero Complex – greenschists; CNRc: carbonate schists; CNRa: marbles and phyllites; MPB: marbles; QLN: quartzites;TIN: serpentinite schists;GSE: gypsum;BCC: carbonate breccias (carniole).

3 Materials and Methods

3.1 UAV Photogrammetry and DTM Generation

To overcome the limitations of regional 5x5 m Digital Terrain Models (DTMs), a high-resolution survey was conducted using a DJI Mavic 3 Enterprise drone. The survey involved four flights capturing over 700 images with at least 80% overlap. An RTK antenna provided centimeter-level accuracy for image positioning. Processing via Structure from Motion (SfM) algorithms generated a point cloud with a density of 100 pts/m², which was then converted into a 0.50x0.50 m resolution DTM for precise geomorphological mapping and numerical modeling of the dynamic of the events.

3.2 Susceptibility Mapping (RES Method)

The Rock Engineering System (RES) method (Hudson 1992) is a semi-quantitative approach based on the construction of an interaction matrix, designed to analyse complex engineering–geological problems by explicitly accounting for the mutual influence among controlling parameters. The method relies on expert-based scoring of pairwise interactions, commonly through the Expert Semi-Quantitative (ESQ) procedure, which assigns values from 0 (no interaction) to 4 (critical interaction).

In this study, RES was applied to assess debris-flow susceptibility in the Fenils catchment. A selected set of key geological, geomorphological, topographic, and hydrological factors was inserted along the main diagonal of the interaction matrix (Table 1), while off-diagonal cells were populated with directional influence scores. Row sums (“cause”) quantify the degree to which each parameter influences the system, whereas column sums (“effect”) measure how strongly each parameter is influenced by the others. The resulting cause–effect diagram allows identification of dominant and subordinate factors within the system.

From the interaction matrix, weighting coefficients (scaled from 0 to 100) were derived for each parameter. These coefficients were subsequently combined with the corresponding thematic layers to compute a debris-flow propensity index (DfPI), expressed as the weighted sum of the predisposition scores for each mapping unit (Bonetto et al. 2021; Vianello et al. 2023;Cantonati et al. 2025). The spatial implementation of this index provides the basis for the debris-flow susceptibility map of the study area.

For the Fenils basin, the implementation follows approaches previously tested in upper Susa Valley and relies on open-source datasets from regional geoportals, processed primarily in QGIS. Five predisposing factors are considered (Table 1): lithology, slope, sediment connectivity, land use, and fracturing or landslide activity. Because bedrock outcrops and Quaternary deposits respond differently to these controls, two separate interaction matrices are constructed—one for rock outcrops (where fracture intensity is central) and one for unconsolidated deposits (where landslide activity state serves as a proxy for material cohesion and remobilisation potential). Lithologies are classified according to mechanical strength and weathering potential; deposits are grouped by genetic and textural characteristics. Slope is discretised into classes, recognising that debris flows are most favoured at intermediate-to-high gradients (around and below ~35°), whereas very steep slopes tend to promote rockfall-dominated processes. Connectivity (Borselli et al. 2008;Cavalli et al. 2013;Crema et al. 2015) is quantified using an index-based approach (SedInConnect), thereby distinguishing sediment sources that are efficiently coupled to the main channel from those that are effectively disconnected. Land-use classes are interpreted in terms of erodibility and vegetation protection.

Table 1. Interaction matrix used for the evaluation of DfPI in the Fenils watershed.

Outcrops bedrock								
	1	**2**	**3**	**4**	**5**	**Cause (C)**	**C+E**	**a_i**
1	**LITHOLOGY**	2	2	1	1	6	10	3.57
2	0	**SLOPE**	4	3	0	7	17	6.07
3	0	3	**SEDIMENT CONNECTIVITY**	2	1	6	18	6.43
4	1	2	2	**LAND USE**	0	5	12	4.29
5	3	3	4	1	**FRACTURING**	11	13	4.64
Effect (E)	4	10	12	7	2	/	70	
Quaternary deposit								
	1	**2**	**3**	**4**	**5**	**Cause (C)**	**C+E**	**a_i**
1	**DEPOSIT**	2	2	2	2	8	19	4.85
2	4	**SLOPE**	4	3	3	14	23	5.87
3	3	3	**SEDIMENT CONNECTIVITY**	2	3	11	21	5.36
4	1	2	2	**LAND USE**	1	6	16	4.08
5	3	2	2	3	**LANDSLIDE ACTIVITY**	10	19	4.85
Effect (E)	11	9	10	10	9	/	98	

3.3 Rainfall Analysis and HEC-RAS Modeling

To define the potential magnitude of the events in the study area, rainfall data from 25 regional grid cells (dataset ARPA Piemonte) were processed using the Gumbel method to construct intensity-duration-frequency curves for return periods (Gumbel 1941) of 20, 50, 100, and 200 years. Concentration times (t_c) were calculated using Kirpich (1940) and Chow (1959) formulas, with the more conservative Kirpich value (approx. 4.2 minutes) adopted to model peak flow rates.

Numerical simulations were performed using HEC-RAS 6.5. The debris flow was modeled as a Newtonian fluid, a conservative choice that maximizes predicted velocities and runout distances by ignoring internal friction. Twelve scenarios were simulated based on hydrographs derived from Rational, Takahashi Volumetric methods (1978).

4 Results

4.1 Susceptibility and Geomorphological Map

The RES analysis produced a susceptibility map showing a medium-to-high trend that increases toward the head of the valley (Fig. 2). Extremely high values were identified in the sub-basin of the Rio Inferno, precisely where the debris flow currently intercepts the buried roadbed.

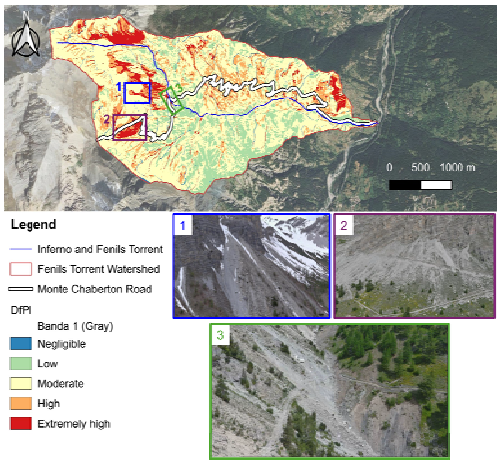


Fig. 2 DfPI map and reconstruction of the source areas within the Fenils Torrent watershed.

4.2 Numerical Simulation Outcomes

HEC-RAS simulations predicted maximum flow velocities of up to 15 m/s in the steepest channel sections. The simulated inundation areas varied significantly depending on the return period and the method adopted, as shown in Fig. 3. The results consistently indicate that debris flows affect the same road segment that is currently buried, thereby supporting the reliability of the model.

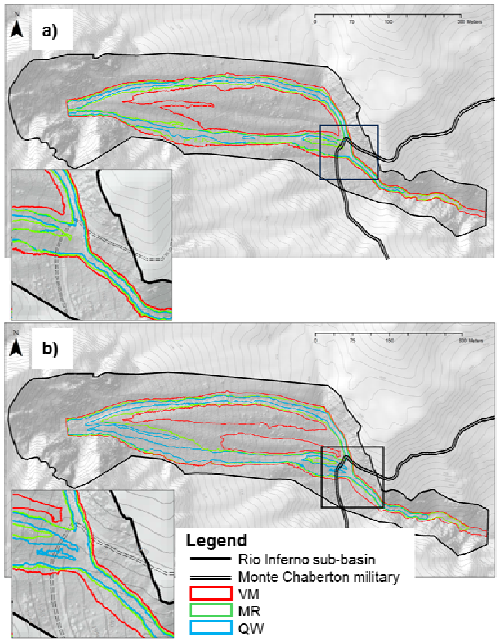


Fig. 3Inundation maps obtained from HEC-RAS under different discharge scenario: the volumetric method (VM), the Rational Method (RM), and the water discharge approach (QW), for return periods of (a) 20 years and (b) 200 years (Turbessi et al.2025).

5 Discussion and Conclusion

The Rio Fenils watershed represents a highly active geomorphological system, where fractured dolomitic slopes continuously supply coarse debris that is readily mobilized during intense summer rainfall events. Grain-size analysis confirms that these processes can be classified as granular debris flows, with approximately 65% of clasts ranging from decimetric to metric sizes, indicating a high transport capacity and significant impact potential. The estimated volumes, on the order of 5,000 m³ for the Rio Inferno sub-catchment alone, combined with the steep channel gradients, result in extremely rapid flow dynamics, with velocities that can reach values consistent with highly hazardous debris-flow processes.

The combined results of susceptibility mapping and numerical modeling highlight a strong spatial coherence between areas characterized by high DfPI values and the sectors affected by recent debris-flow activity. In particular, the Rio Inferno sub-basin emerges as the most critical sector, where both

morphometric conditions and sediment availability favor frequent reactivation. The HEC-RAS simulations further confirm this behavior, showing that modeled flow paths and inundation areas consistently overlap with the currently damaged segment of the former Chaberton military road. This agreement supports the reliability of the adopted modeling approach, despite the simplifying assumptions and demonstrates its effectiveness as a preliminary tool for hazard assessment in data-scarce alpine environments.

From a risk management perspective, the high recurrence and magnitude of debris-flow events suggest that purely local and rigid structural solutions, such as gabions or small-scale reinforcements, may provide only temporary mitigation. Instead, more flexible and adaptive solutions should be considered. Options such as elevated structures (e.g., suspension bridges) or redesigned crossings (e.g., a series of fords) could better accommodate the dynamic nature of the system, reducing maintenance requirements and improving long-term resilience. These solutions should be evaluated within a broader framework that considers not only hydraulic performance but also geomorphological evolution and sediment continuity.

Overall, the study highlights the importance of adopting integrated, multiscale approaches for the management of debris-flow hazards in mountain environments. This is particularly relevant in the context of ongoing climate change, which is expected to increase the frequency and intensity of triggering rainfall events, as well as sediment availability. In this framework, the proposed methodology can support more informed decision-making and contribute to the development of sustainable risk mitigation strategies in alpine regions.

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