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Changes in alpine routes in terms of difficulty, hazard and accessibility: a case study in the area of Mount Adamello and Corno Baitone (Northern Italy)

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High-altitude mountain regions, such as the Alps, are highly sensitive to climate change, experiencing global-average warming. This phenomenon is leading to significant modifications of the Alpine environment, increasingly exposing mountaineers to natural hazards. Therefore, this study aims to: (i) assess climate change impacts on glacial and periglacial environments, along the main mountaineering routes of Mount Adamello and Mount Baitone (Northern Italy), based on the experience of mountaineers across three decades; and (ii) evaluate potential inconsistencies between perceived hazard and quantitatively assessed hazard for specific geomorphological processes. The analysis integrates citizen science with geomorphological and geological-technical surveys and analyses.

Questionnaires were developed and administered to key stakeholders (alpinists, hut keepers, mountain guides, etc.) to assess perceived route difficulty, changes in accessibility and objective hazard (rockfalls, earth slides, glacier instabilities, worsening of route conditions), for these itineraries over the past three decades (1996–2005, 2006–2015, and 2016–2025). Field surveys were conducted in the Mount Adamello and Baitone areas to map glacial, periglacial, and gravity-driven slope processes. At representative locations, rock slope instability was evaluated using the Markland Test, to identify kinematically feasible failure mechanisms, and the Geological Strength Index (GSI), to assess rock mass quality. Rockfall hazard was assessed using the Rockfall Hazard Assessment Procedure (RHAP), based on rockfall simulations performed along selected 2D profiles intersecting hiking routes. RHAP outputs were used to delineate five hazard zones from very low (1) to very high (5) according to block runout distributions. The final hazard classification was refined by combining RHAP zoning with GSI and Markland Test results. These quantitative results were compared with the questionnaire results, to assess the consistency between scientific evidence and users' perception.

Through RHAP, all the routes analyzed in the Adamello area were classified as Zone 5 (very high hazard), while at Baitone as Zone 4 (high hazard). Questionnaire results indicate a general

increase in perceived difficulty over time, with reduced accessibility – associated with increasingly long and hazard-exposed ascents – mainly driven by glacier retreat. Rock slope instability remains the most frequently reported hazard, although the relative importance of other hazards has increased over decades. Focusing on rock slope instability, its recognition ranged from 45% to 73% across Adamello routes, compared to no recognition at Baitone. This result suggests, for most routes, a little consistency between scientifically defined hazards and users' average hazard perceptions. Rather, a direct correlation exists between perceived difficulty and perceived objective hazards. In detail, routes with high technical difficulty are associated with increased recognition of objective hazards, suggesting that experience in challenging environments enhances risk perception. This trend is further confirmed by expert groups, such as mountain guides and rescue personnel, whose assessments generally align closely with geomorphological evidence.

Understanding climate-driven modifications in high-mountain environments through both geological–technical analyses and citizen science, as well as identifying the differences between actual hazard and perceived hazard, is crucial for improving risk communication and prevention strategies, route management, and to promote conscious, sustainable, and safe use of high-altitude terrains.