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博士（環境科学）

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An integrated analysis of snow and ice avalanche hazards in the Annapurna Conservation Area,
Nepal Himalaya

(ネパール, アンナプルナ保全地域における雪崩ハザードの統合的分析)

The cryosphere in High Mountain Asia (HMA) serves not only as a vital source of water for the populations living downstream, but also possesses the potential for hazards. One such hazard, avalanches, has received inadequate attention, as the complex relationship between climate and potential triggers is not well understood due to a lack of long-term observations, inaccessibility, severe weather conditions, and financial and logistical constraints. This study aims to address this gap by focusing on the current state of knowledge regarding avalanche hazards in HMA. It examines the research and societal gaps, proposes potential future research directions and mitigation strategies, and develops an avalanche susceptibility map for the Annapurna Conservation Area (ACA). This study also delves deeper into the impact of avalanches on lives, livelihoods, and vulnerable communities in the ACA, and evaluates the existing disaster risk management strategies at the local level.

First, exiting literature was examined, encompassing the period between the late 20th century and June 2022, with the aim of identifying research and societal gaps and proposing future research directions and mitigation strategies. In addition to scientific literature, technical reports, newspapers, social media, and other local sources were consulted to create a comprehensive, open-access, version-controlled database of avalanche events and their associated impacts. The avalanche susceptibility map of the Annapurna Conservation Area was developed using a Multi-Criteria Decision Analysis (MCDA)–Analytical Hierarchy Process (AHP) model within a Geographic Information System (GIS) environment. The terrain parameters, including slope, curvature, terrain roughness, elevation, and aspect, were derived from ASTER GDEM V3 (ASTGTM), as well as ground cover data from ESRI land use/land cover, lithology (NTB), and meteorological data, such as air temperature and precipitation datasets from the Department of Hydrology and Meteorology (DHM), Nepal. The relative weights of the criteria and sub-criteria were determined using MCDA-AHP, which was based on expert judgment, literature, and historical avalanche events.

Two areas, the Annapurna Base Camp (ABC) route (Area 1) and the Kobang area (Area 2) in the ACA, were considered for the questionnaire survey to analyze exposure to avalanche hazards. A total of 29 questions about avalanches were asked in 24 and 69 households in Areas 1 and 2, respectively. Focus group discussions were conducted in both areas with relevant stakeholders to analyze existing disaster management strategies. A total of

681 avalanches have been documented in eight countries, resulting in the loss of 3131 human lives. Afghanistan experienced the highest number of avalanche fatalities with 1057 casualties, followed by India with 952 and Nepal with 508. Furthermore, 564 individuals perished while attempting to climb peaks that were higher than 4500 m a.s.l., with one-third of them serving as guides or porters. Although this represents a lower fatality rate than in the less populated European Alps, for instance, the number of affected individuals who did not willingly expose themselves to avalanche risk is noteworthy at 25. The region lacks comprehensive adaptation or mitigation measures for avalanches, which typically rely on local and indigenous knowledge that has been adapted to modern technology. Considering the significant fatalities and long-term local impacts of avalanches, further development of adaptation measures, such as hazard zonation maps, based on historical event datasets and modeling efforts, is recommended. However, this should be done in collaboration with communities, local governments, and civil society stakeholders, and by recognizing and building upon the existing knowledge in the region. Future research should focus on identifying the trends and drivers of avalanches in this region.

The evaluation of the susceptibility map was performed using the natural breaks method, which yielded five distinct zones: very low, low, moderate, high, and very high susceptibility. The high and very high zones accounted for approximately 37.0% of the total area, while the moderate zone covered 23.9%. The validation was carried out using an avalanche inventory map comprising 120 cases derived from documented avalanche locations, field surveys, and satellite imagery. The prediction accuracy was evaluated using the area under the ROC curve (ROC-AUC) method, resulting in an approximate accuracy rate of 89%. The findings of this comprehensive hazard analysis have the potential to enhance preparedness and mitigation planning in the study area.

The results of the social survey conducted in the ABC route (Area 1) and Kobang area (Area 2) revealed that 133 individuals in Area 1 and 313 individuals in Area 2 were continually exposed to the threat of avalanches. The exposed population primarily consisted of migrant workers in Area 1, while most of the local population, along with some migrant workers engaged in agricultural activities, was highly vulnerable to avalanche hazards in Area 2. Both areas experienced avalanche impacts, resulting in a significant number of casualties and livestock losses, particularly in Area 2. Area 1 demonstrated better preparedness and mitigation efforts than Area 2. While a certain percentage of households in both areas mentioned implementing avalanche mitigation measures, a smaller proportion actually took steps towards prevention and mitigation. Focus group discussions revealed a lack of concrete mitigation mechanisms in both areas. However, community members in Area 1 exhibited greater awareness and proactive measures, such as constructing control structures to mitigate avalanche impacts. By contrast, Area 2 predominantly relied on short-term compensation measures, highlighting the need for more robust mitigation strategies.

This study advances our comprehension of avalanche risks and introduces an avalanche susceptibility map as a fundamental resource for future investigations. An extensive social survey was executed in two areas prone to avalanches to explore the prevailing avalanche scenarios, coping mechanisms, and the roles of local authorities in mitigating these hazards. This study suggests a comprehensive approach that incorporates avalanche susceptibility modeling and socioeconomic surveys to gain in-depth insights into avalanche dynamics, thereby facilitating the formulation of effective policies and control measures. These findings constitute the foundation for future research and policy development to enhance the resilience of avalanche-prone communities.