Title	An integrated analysis of snow and ice avalanche hazards in the Annapurna Conservation Area, Nepal Himalaya [an abstract of entire text]
Author(s)	ACHARYA, Anushilan
Description	この博士論文全文の閲覧方法については、以下のサイトをご参照ください。 https://www.lib.hokudai.ac.jp/dissertations/copy-guides/
Degree Grantor	北海道大学
Degree Name	博士(環境科学)
Dissertation Number	甲第16072号
Issue Date	2024-09-25
Doc URL	https://hdl.handle.net/2115/93454
Type	doctoral thesis
File Information	ACHARYA_Anushilan_summary.pdf

学 位 論 文 内 容 の 要 約
博士（環境科学） 氏 名 ACHARYA Anushilan

学 位 論 文 題 名

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）

Introduction

High Mountain Asia (HMA), a unique region encompassing the Hindu Kush Himalaya (HKH) and the Tien Shan mountains, is often referred to as the "Third Pole." It holds the distinction of having the largest expanse of snow, glaciers, and permafrost outside the North and South Poles. Spanning 4.2 million km^2, with 1.4% glaciated and 0.76 km^2 covered in perennial snow (Bajracharya et al. 2015), this region acts as a vital water tower, supplying water to 10 major river systems and supporting approximately 1.9 billion people downstream, primarily in China, Nepal, and India (Wester et al. 2019).

Moreover, this region is home to four global biodiversity hotspots and boasts 330 crucial bird areas (Chettri et al. 2008), making it vital for sustaining ecosystems and biodiversity. Its significance extends further as it ensures water availability for agriculture, domestic needs, industry, and hydropower, providing essential ecosystem services to support the livelihoods of 240 million people in mountainous and hilly regions (Immerzeel et al. 2010; Wester et al. 2019).

However, the cryosphere in the HMA presents not only valuable natural resources, but also the potential for numerous mountain hazards, such as glacial lake outburst floods and avalanches, and indirect impacts, such as disrupted irrigation channels, receding glaciers, and changing climate patterns (Richardson and Reynolds 2000).

While High Mountain Asia (HMA) serves as a lifeline for millions of people, ensuring water availability and fostering biodiversity, it remains vulnerable to the recurrent threat of avalanches. A comprehensive overview of the state of knowledge regarding snow and ice avalanches in the HMA is lacking. The Annapurna Conservation Area lies within this region with a rich ecosystem that boasts diverse flora and fauna that are susceptible to avalanche hazards. Only a few fatalities have been reported (McClung 2016; Thakuri et al. 2020). Earthquake-triggered ice avalanches in Langtang have limitations (for example, Fujita et al. 2017). However, no assessment of the entire region has been conducted, even though avalanches are a prominent cryospheric hazard. Studies related to avalanche hazards, in terms of mapping, prediction, and modeling, have concentrated mainly on the Western Himalayas (Ganju and Dimri 2004; Bühler et al. 2013; Kumar et al. 2017), but very few studies have been conducted in the eastern and central Himalayas (Sherpa et al. 2019; Tuladhar et al. 2021). The complex nature of the terrain, high altitude, and financial and logistic constraints have exacerbated these studies.

Recent events such as the Seti flood due to a suspected avalanche in Annapurna IV in 2012 killed 72 people (Kargel et al. 2014), the snowstorm in 2014 led to a series of avalanches that claimed 43 lives (Thakuri et al. 2020), and the avalanche in the ABC route (Deurali) in January 2021 killed seven people. These examples demonstrate the urgency of this research. The frequency and magnitude of such disasters are on the rise, as evidenced by the area that experienced a massive avalanche with significant livestock fatalities in Kobang, Mustang in November 2021, only to face another avalanche in March 2022 (Shrestha 2022).

With the increasing movement of people for recreational and research purposes in the inner part of the Himalaya in recent decades, avalanches have affected not only locals but also other individuals who encounter numerous avalanches on their way. Avalanches have significantly impacted the livelihoods of surrounding communities, the natural environment, and the socioeconomic stability of the region. Therefore, it is crucial to conduct avalanche hazard analysis in the Annapurna Conservation Area (ACA).

Objectives

The overall objective of this research was to conduct an avalanche hazard analysis of the High Mountain Asia (HMA) region, with a particular focus on the Annapurna Conservation Area (ACA), to enhance the resilience of mountain communities. The specific objectives are: (1) to analyze the available avalanche hazard literature to identify research and societal gaps and propose future directions of research and mitigation strategies; (2) to derive an avalanche hazard susceptibility map of the ACA using Multi-Criteria Decision Analysis (MCDA)-Analytical Hierarchy Process (AHP) in a GIS environment; (3) to analyze the exposure of life, livelihoods, and infrastructure to avalanche hazards and vulnerability to avalanche hazards in the ACA; and (4) to analyze the existing disaster risk management strategy at the local level in the ACA.

Study areas and methodology

High Mountain Asia (HMA)

High Mountain Asia (HMA) consists of 22 subregions, namely: Dzhungarsky Alatau, Eastern Tien Shan, Central Tien Shan, North/Western Tien Shan, Pamir Alay, Western Pamir, Eastern Pamir, Eastern Hindu Kush, Karakoram, Western Himalaya, Central Himalaya, Eastern Himalaya, Western Kunlun Shan, Eastern Kunlun Shan, Altun Shan, Tibetan Interior Mountains, Gangdise Mountains, Nyainqentanglha, Tanggula Shan, Hengduan Shan, Eastern Tibetan Mountains, and Qilian Shan with an area coverage of about 4 million km^2 ((Bolch et al. 2019). It is the largest source of cryosphere outside the polar regions (Bolch et al. 2019).

It is characterized by extreme topographic and climatic heterogeneity. The climatic patterns are predominantly influenced by the East Asian and Indian monsoon systems, which contribute the majority of precipitation to the central and eastern Himalayas from June to

September (Bookhagen and Burbank 2006), with annual total precipitation up to 3,000 mm (Bookhagen and Burbank 2010; Maussion et al. 2014). Conversely, the western Himalaya experiences intense winter snowfall due to westerly disturbances, with over 80% of the total precipitation typically ranging between 1,000 mm and 2,000 mm annually (Barlow et al. 2005; Bookhagen and Burba et al. 2014), but the monsoon-influenced central and eastern areas experience comparatively drier winters (Shrestha et al. 2000). The complex topography of the region creates annual temperature differentials of up to 40°C within short distances, and precipitation gradients vary significantly across mountain ranges (Shrestha et al. 2012).

More than one billion people in HMA are at risk of exposure to increasingly frequent and severe natural hazards. Multiple hazards, such as floods, flash floods, avalanches, landslides, droughts, and earthquakes, are very common in the region. The multi-hazard environment in the region creates cascading events that link the upstream and downstream areas, often with transboundary impacts (Vaidya et al. 2019).

Annapurna Conservation Area (ACA)

The Annapurna Conservation Area is Nepal's largest protected area, with a geographic extent of 28°47′N to 28.78°N latitude, 83°58′E to 83.97°E longitude, and an area coverage of 7,629 km² in the Annapurna range of the Himalaya. The elevation ranges from 790 m to the peak of Annapurna I at 8,091 m, stretching across the Manang, Mustang, Kaski, Myagdi, and Lamjung districts. It was established in 1985, gazetted in 1992, and managed by the National Trust for Nature Conservation (NTNC).

Five settlements (Ghattekhola, Naurikot, Larjung, Kobang, and Chhaktang) in Thasang Rural Municipality and five settlements (Annapurna Base Camp (ABC), Machhapuchhre Base Camp (MBC), Deurali, Himalaya, and Dovan) in Annapurna Rural Municipality were considered for detailed avalanche studies with research field visits in May 2023. Avalanche locations in and nearby these settlements were documented based on avalanche debris and scars, and the local population showed various avalanche locations where they often encountered avalanches.

Methodology

To examine the overview of avalanche hazards in the HMA region, information on avalanches was collected from different sources, including peer-reviewed articles, newspaper articles, technical reports, social media, and interactions with people in high mountain catchments in the region. The period covered ranged from the earliest records of deaths in the late 20th century to June 2022.

An 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. 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 from the Department of Hydrology and Meteorology (DHM), Nepal. The relative weights of the criteria and sub-criteria were determined using MCDA-AHP, based on expert judgment, literature, and historical avalanche events.

Two areas, i.e., the Annapurna Base Camp (ABC) route (Area 1) and Kobang area (Area 2) in the ACA, were considered for a questionnaire survey to analyze exposure to avalanche hazards. Questionnaire sheets with answers on 30 different questions focused on socioeconomic information, impacts of avalanches, prevention and mitigation efforts, and general information were collected from 24 and 69 households in Areas 1 and 2, respectively, to analyze the existing understanding of avalanche hazards and their efforts to mitigate or cope with this hazard. Focus group discussions (FGDs) were conducted with relevant local stakeholders. In Area 1, representatives from the Annapurna Conservation Area (ACAP), Tourism Management Committee (TMC), Annapurna Rural Municipality (ARM), and Century Youth Club (CYC) were invited to participate in focus group discussions. The Thasang Rural Municipality (TRM), Kobang Ward, and the Conservation Area Management Committee (CAMC) were invited to Area 2.

Results

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 (952) and Nepal (508). Furthermore, 564 individuals perished while attempting to climb peaks 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, the number of affected individuals who did not willingly expose themselves to avalanche risk is noteworthy. The region lacks comprehensive adaptation or mitigation measures for avalanches, which typically rely on local and indigenous knowledge 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, as well as by recognizing and building upon existing knowledge in the region. Future research should focus on identifying the trends and drivers of avalanche occurrence in this region.

The susceptibility map was derived using the natural break 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, whereas the moderate zone accounted for 23.9%. Validation was conducted using an inventory map of 120 cases derived from documented avalanche locations, field surveys, and satellite imagery. 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 this study area.

The results of the social survey conducted on 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. In contrast, most of the local population, along with some migrant workers engaged in agricultural activities, were highly vulnerable to avalanche hazards in Area 2. Both areas experienced avalanche impact, resulting in a considerable number of casualties and livestock losses, particularly in Area 2. Area 1 showed better preparedness and mitigation efforts than did Area 2. While a certain percentage of households in both areas mentioned implementing avalanche mitigation measures, a smaller proportion took steps towards prevention and mitigation. The focus group discussions revealed a lack of concrete mitigation mechanisms in both areas. However, the community members in Area 1 showed 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.

Discussion

Comprehensive records of observed avalanches in HMA were gathered, including those that did not have any notable impact on livelihoods or infrastructure and information on impacts for those that did. Until the 2010s, rarely more than one event was recorded every two years in individual mountain ranges, which increased to more than four per year in the Pamir and more than one in the Hindu Kush, largely due to the commencement of a dedicated avalanche monitoring program. Records have also increased elsewhere, but it is impossible to say whether an increase in avalanche activity, increased exposure, or simply an increase in reporting (e.g., the advent of social media resulting in more coverage in the local news) is responsible. Records show that relying solely on peer-reviewed publications results in a considerable underestimation of events, capturing only 6% of all avalanches and 23% of all recorded fatalities. Relying on various news sources, which, however, often have conflicting documentation of what happened, requires a lot of cross-checking work and technical reports by agencies working in hazard management in the region.

Total fatalities in the region since the early 1970s ended up at an average of 62 people killed each year, or 74, when we included deaths during mountaineering. Records in the Alps, an area considerably smaller and less populated than the HMA, show ∼100 people per year who lost their lives between 1937 and 2015 (Techel and Schweizer 2017). However, while in the Alps between 72% and 97% of deaths are related to mountaineering or recreation, this number is reversed in HMA (15%) and becomes even smaller (10%) when we consider that porters and guides died during work rather than recreation. In Switzerland, avalanche victims between 1946 and 2015 accounted for 37% of all natural hazard fatalities, more than any other. For HMA, insufficient comprehensive data exist for other hazards to make such a comparison.

However, data from GLOFs suggest a considerably lower number of deaths (907, excluding the Kedarnath event) for a much longer period (1833–2022) in the same region (Steiner and Shrestha 2022). Landslides claim a lot more deaths in monsoon-dominated India (~5000 between 1998 and 2018 excluding the Kedarnath event; Martha et al. 2021) and Nepal (2179 between 1978 and 2005; Petley et al. (2007). Records for countries entirely in the HMA suggest 67 deaths in Afghanistan, 50 in Bhutan, 809 in Nepal, and 75 in Tajikistan between 2004 and 2010 (Petley 2012). The relative lack of recreational sports in the avalanche-prone territory in the region, therefore, makes avalanches relatively less deadly than in the Alps and much less deadly than landslides in the region, but considerably more so than GLOFs, a high mountain hazard that has received relatively more attention in the literature (Emmer et al. 2022).

The data suggest that 564 people died in avalanches while mountaineering in HMA, 191 (34%) of whom were hired personnel, such as guides and porters. This emphasizes the danger of the job, which is perceived as an important opportunity in some regions, especially Nepal. An earlier study found slightly more fatalities for HMA (616), stemming from undocumented sources beyond peaks above 8000 m (McClung, 2016).

Earlier works in North America (Schauer et al. 2021), northern Europe (Fitzharris and Bakkehøi 1986; Hancock et al. 2021), and the Alps (Jomelli et al. 2007) have shown the potential of investigating precursor meteorological data for avalanche prediction using avalanche databases. In the HMA, such forecasting exists only in the Indian western Himalaya. The present database allows for the first analysis of these links. So far, an inventory of avalanches without significant recorded impacts for countries other than Afghanistan is missing to make such an analysis robust. With such monitoring efforts being highly labor intensive and not possible for past events, the potential of remote sensing data would need to be further exploited, so far only done for limited areas in the region (Eckerstorfer and Grahn 2021; Caiserman et al. 2022). Satellite imagery can scale up avalanche monitoring, mainly owing to the availability of many satellite datasets, including both optical and radar. Owing to the challenging nature of interpreting radar data for different avalanches (Eckerstorfer et al. 2016; Eckerstorfer and Grahn 2021), databases relying on field observations are necessary for validation. Combining the available events database with past regional climate data would allow one to better understand the climatology of avalanches in the HMA, an approach already employed in the Alps (Eckert et al. 2010). This could allow for a better understanding of the link between a changing climate and the occurrence of avalanches, which so far have only been investigated for a field site in India (Ballesteros-Cánovas et al. 2018) and China (Hao et al. 2023).

The GIS-based MCDA technique was applied to develop an avalanche hazard susceptibility map for the Annapurna Conservation Area. AHP was chosen over a wide variety of MCDA techniques because of its proven efficiency in integrating diverse datasets, ease in obtaining weights for many criteria, and improvement in decision-making processes. It is widely used and accepted in the field of natural hazards (Selcuk 2013).

The resulting susceptibility map showed high and very high susceptibility areas concentrated along the Annapurna Range within the ACA. More avalanche susceptibility is observed in the ACA's Middle Eastern and Western areas. These zones pose significant risks to nearby settlements, including ABC, MBC, Deurali, and Himalaya, where recurring fatal and non-fatal avalanche incidents are reported, particularly during the winter, pre-monsoon, and post-monsoon seasons.

ASTER DEM V3 data were used to derive terrain parameters relevant to avalanche formation. The ALOS PALSAR DEM 12.5 m, with its higher resolution was initially considered for the study. However, it was unavailable in the study area and, thus, could not be used. Consequently, a susceptibility map was developed using other DEMs, including NASADEM and Copernicus DEM. Ultimately, the best results were achieved using ASTER DEM. Although higher-resolution data could have improved the accuracy, it also posed the risk of detecting more avalanches (Bühler et al. 2013). Moreover, air temperature data were only available for three stations, necessitating temperature lapse rates to estimate air temperatures at the remaining stations across the study area. The mean annual temperature lapse rate of -5.2°C/km (Kattel et al. 2013) was applied to derive temperature datasets for all remaining weather stations in the ACA from 1992 to 2022.

During avalanche inventory map preparation, field visits were conducted to identify avalanche locations. Despite the challenges posed by inaccessible terrain, this study meticulously recorded the GPS coordinates in each area and cross-verified them against runout zones. Google Earth was used to improve the accuracy of the location data.

The ABC Route exhibits a pronounced gender disparity, with males constituting 97% of the population and females constituting only 3%. This skew suggests that males predominantly engage in guesthouses, which are the main livelihood of this area, indicating a male-dominated workforce. In contrast, the Kobang Area shows a nearly equal distribution of males and females, with 49.8% males and 50.2% females. This balance depicts a diverse community with multiple livelihoods, reflecting a residential or family-oriented setting.

The age demographics also differed significantly between the two areas. ABC Route primarily attracts adults or a working-age population within the 30-60 age bracket, confirming job opportunities that appeal and retain this age group, while less accommodating conditions for younger and older demographics due to the unavailability of necessities. Conversely, in the Kobang Area, a broad age distribution, including a considerable proportion of both very young and elderly residents, is indicative of an environment with facilities and a lifestyle supporting all age groups.

Furthermore, the impact of avalanches varies markedly between the two areas. In the ABC Route, avalanches mostly affect the tourism sector, with some repercussions, such as damage to guesthouses (15) and human injuries (10). Kobang experienced a broader range of avalanche impacts, including considerable damage to houses (69), human fatalities (3), injuries (6), animal deaths (249), crop damage (1.58 hectares), and destruction of animal sheds (4 incidents). These figures demonstrate that Kobang's diverse livelihood patterns were consistently and severely affected by avalanche activities, pointing to the need for targeted disaster management, support systems, and response strategies in the area. A study based on case material from 50 households in the settlements of Phalyak and Dhakarjong in Kagbeni VDC, Mustang district near the same area, collected between 2013 and 2015, showed that households in these settlements have diversified their livelihood options. Previously dominated by agriculture and livestock raising, they have now expanded to include apple farming (for cash income), vegetable farming, and tourism-based activities in response to various shocks and stressors (Fort 2015).

Conclusions

A comprehensive investigation incorporating all accessible snow and ice avalanche records from the High Mountain Asia (HMA) region was conducted based on journal articles, technical reports, and newspapers. In addition, previous scientific research, indigenous knowledge, and existing or active adaptation and mitigation strategies were investigated.

The developed avalanche database spans half a century between 1972 and 2022, and records 681 individual events (88% snow and 1% ice avalanches, excluding mountaineering accidents with high peaks). Of these, 21% had some recorded impact and 17% fatalities were recorded. Avalanches killed more than 3100 people, more than 62 per year on average, most of them in Afghanistan (1057; 34%), India (952; 30%), and Nepal (508; 16%). This suggests that avalanches are a deadly hazard in high mountain environments in the region, causing considerably more fatalities than glacial lake outburst floods. On average, each avalanche in our database suggested 27 people killed, making it an exceptionally high-impact event. Approximately 1900 livestock killed in 24 events are also noteworthy, as this impact on livelihoods has been mentioned as an especially problematic aspect of the hazard in the region. More than 500 people were killed in avalanches while climbing mountain peaks above 4500 m a.s.l., one-third of whom were porters or guides employed during these endeavors.

Scientific studies on avalanches with field investigations are limited to research stations on the Tibetan Plateau and the Indian western Himalaya. As a result, modeling studies conducted in several locations still need to be more extensive, as information on snowpack and local climate is lacking.

Several adaptation and mitigation measures have been implemented. In India and China, this project has received large-scale funding for specific regions where avalanches have been identified as potential threats to road infrastructure. This includes dedicated monitoring programs that coordinate with scientists and investments in state-of-the-art structural measures. However, non-governmental efforts have been successful. The monitoring of avalanches in Afghanistan is unparalleled in the region and conducted by local stakeholders. It is the only country that records individual avalanche events, irrespective of their impact, an effort that is incredibly valuable for future studies investigating meteorological drivers. Other examples of locally carried initiatives, such as harvesting avalanche deposits for meltwater to be used in high mountain irrigation in Pakistan, are also a testament to the existence of local solutions to address hazards that should be investigated for potential scaling to other localities in the future.

An avalanche susceptibility map with five zones (very low, low, moderate, high, and very high) was developed using MCDA AHP within a GIS environment using terrain (ASTER DEM, NTB, and ESRI LULC) and meteorological (DHM) factors. The very low, low, moderate, high, and very high zones comprised of 15.7%, 24.0%, 23.3%, 21.3%, and 15.6%, respectively. The high and very low values lie mostly in the middle region of the ACA along the Annapurna Range. The derived avalanche susceptibility map was validated through ROC curve analysis, which yielded a prediction rate of 89%, indicating good alignment with documented avalanche locations.

In the ABC Route, 62.5% of the 24 households claimed that they were damaged by avalanches at some point. In Mustang, 82.9% of households claimed that their houses were damaged due to avalanches—no human casualties in ABC Route, but three deaths in Mustang. The ABC Route also sustained ten injuries, and respondents in the Kobang Area claimed six injuries. The ABC Route was severely affected in terms of tourism flow, whereas the Kobang Area was affected in terms of agricultural activities.

It is crucial to note that prevention and mitigation efforts in both areas are insufficient and nonexistent. However, the ABC Route is slightly more aware of the situation and makes personal contributions to sustaining its livelihood. It is important to find that relevant stakeholders should pay more attention to minimizing the risks posed by avalanches, leaving the population and infrastructure vulnerable.

ACA is one of the nation's major tourism hubs, and the tourism industry is the primary source of income. Avalanches affect the lives and livelihoods of the local population in both areas, subsequently affecting the country's revenue. The relevant authority should consider it seriously and plan and design policies and control measures to minimize the damage caused by avalanches.