

Article

Snow Avalanche Hazards and Avalanche-Prone Area Mapping in Tibet

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Abstract: Snow avalanche is one of the major natural hazards in the mountain region, yet it has received less attention compared to other mountain hazards, such as landslides, floods, and droughts. After a comprehensive overview of snow avalanche hazards in Tibet area, the spatial distribution and main driving factors of snow avalanche hazards in the high mountain region in Tibet were presented in the study first. Snow avalanche-prone areas in Tibet were then mapped based on the snow cover distribution and DEM data and were validated against in situ observations. Results show that there are the highest frequencies of avalanche occurrences in the southeastern Nyainqentanglha Mountains and the southern slope of the Himalayas. In the interior of plateau, avalanche development is constrained due to less precipitation and much flatter terrain. The perennially snow avalanche-prone areas in Tibet account for 1.6% of the total area of the plateau, while it reaches 2.9% and 4.9% of the total area of Tibet in winter and spring, respectively. Snow avalanche hazards and fatalities appear to be increasing trends under global climate warming due to more human activities at higher altitudes. In addition to the continuous implementation of engineering prevention and control measures in pivotal regions in southeastern Tibet, such as in the Sichuan–Tibet highway and railway sections, enhancing monitoring, early warning, and forecasting services are crucial to prevent and mitigate avalanche hazards in the Tibetan high mountain regions, which has significant implications for other global high mountain areas.

Keywords: snow avalanche hazard; avalanche-prone area; field investigation; Sentinel-2; Tibet



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1. Introduction

Landslides, debris flows, avalanches, flash floods, glacial lake outburst floods, mudslides, and rockfalls constitute main natural hazards in the mountain regions [1,2]. Of these, snow avalanches are one of the serious natural hazards that commonly occur in snow-covered mountains, defined as a sudden mass movement of snow and ice on mountain slopes with the downhill trajectory exceeding 50 m, sometimes containing portions of rocks, soil, and vegetation [3,4]. As a natural phenomenon, snow avalanche develops under complex interactions between snowpack, terrain, and weather conditions, usually occurring during or after heavy snowfall [5,6]. As one of the severe nature hazards in snow-covered mountains with steep terrain and low temperature condition, snow avalanches seriously threaten infrastructure, human life, and property in cold mountainous regions throughout the world [7–11]. Under global climate warming, with increasing human activities in alpine mountains, the impact of avalanches on human life and property tends

to intensify. On 31 May 1970, a huge earthquake-induced avalanche occurred on Mount Huascaran, the highest peak of Peruvian Andes, killing 6000 people, making it the largest and deadliest avalanche disaster in the world so far [12]. In the United States, the casualties associated with avalanches in 2021 alone were 37 fatalities (Avalanche.org, 2021) and 127 in Europe (European Avalanche Warning Services, 2021). There have been over 600 recorded fatalities caused by snow avalanches since the mid-1800s and an average of 12.5 persons per year were killed in avalanches in Canada during the 1990s [13]. On 25 April 2015, a series of avalanches occurred at the base camp in the southern Mount Qomolangma (Everest) in central Himalayas triggered by a 7.8-magnitude Nepal earthquake, killing 23 people [14,15]. On 17 January 2023, a catastrophic snow avalanche occurred at the exit of Mount Duoxiongla Tunnel in Milin County of Tibet in eastern Himalayas and caused 28 people death, which is one of the deadliest avalanche-caused casualties in Tibetan history. It was reported that this massive snow avalanche was likely triggered by powerful wind and temperature rising.

Snow avalanches are characterized by seasonality, suddenness, repeatability, and regionality, and they often pose a great threat to transportation, infrastructure, forestry, agriculture, and animal husbandry in the mountain regions. To mitigate and prevent snow avalanche hazards, scientists, engineers, and practitioners have conducted fruitful research and practices on spatial distribution, classification, formation mechanism, prevention and control measures for snow avalanches worldwide [16,17]. Information about avalanche occurrences, locations, and volumes is critical for avalanche warning, hazard zoning, hazard mitigation infrastructure, and risk management [18–20]. This information is collected and mainly reported by observers and ground-based stations. In recent years, remote sensing technology is increasingly used to detect and map snow avalanches due to data availability, spatial coverage and consistency, and excellent spatial, spectral, and temporal resolutions [21–23]. A comprehensive review of optical, lidar, and radar remote sensing for snow avalanches was made by Eckerstorfer et al. [24]. Snow avalanches often occur in cold season and high-altitude mountain regions, where snow cover and related hazards only can be detected by remote sensing approaches due to remoteness, inaccessibility, and harsh climate conditions. In addition, snow avalanche research and observations are highly risky [24,25]. Remote sensing enables objective, safe, and spatially continuous observations of snow avalanches at different spatial scales and platforms. Optical measurement, LiDAR (Light Detection and Ranging), and radar (Radio Detection and Ranging) are three main remote sensing methods to detect snow avalanches and can be mounted at the ground-, air-, and spaceborne platforms [24–27]. Optical remote sensing detects the extent of snow avalanches by using contrast differences between avalanche debris and surrounding land surface, while LiDAR and radar sensors actively emit electromagnetic waves. LiDAR sensor measures a change in snow cover mass balance to detect the areal extent and the volume of avalanches. Radar detects snow avalanches based on the principle that different radar wavelengths are sensitive to different physical snow properties.

The intense tectonic activities and complex geomorphological structure have made the Tibetan Plateau (TP) highly susceptible to mountain hazards, including glacial lake outburst, torrential floods, debris flows, landslides, and avalanches [28]. Snow avalanche is one of the major natural hazards in the high mountain regions in Tibet. Since 1960s, the research on snow avalanches and practice for prevention and control measures have been conducted in Tibet primarily due to the importance of the safety operation of Sichuan–Tibet highway. Wang carried out extensive investigations and in-depth research on snow avalanches in mountain regions in western China and pointed out that wet snow avalanches are more dangerous in southeastern Tibet [29]. Many research institutes of CAS (Chinese Academy of Sciences) have made observations and investigations on snow avalanche hazards in the Hengduan Mountains and along the Sichuan–Tibet highway since 1970s [30,31].

Over the past two decades, the research on snow avalanches in Tibet mainly focused on geohazard prevention and controls for the Sichuan–Tibet highway and the potential impact on the Sichuan–Tibet railway, with more emphasis being placed on hazard risk

assessment and avalanche susceptibility mapping [32–35]. The Sichuan–Tibet highway is 2142 km long section from Chengdu to Lhasa as part of the G318 national highway, which was operational in 1958. The Sichuan–Tibet Railway extends from Chengdu in the east to Lhasa in the west. The railway is 1543 km long and is of strategically great importance for regional socioeconomic development. Because of the complex natural environment in the southeastern TP, the Sichuan–Tibet Railway is at risk of various hazards at different stages of its entire life cycle [36]. The avalanche is among these hazard risks that this mega project has to face. On 28 December 2018, the east section (Chengdu–Ya’an), which is 140 km long, was put into operation, while the west section (Lhasa–Nyingtri), which is 403 km long, became operational on 25 June 2021. The middle section from Ya’an to Nyingtri with 1000 km is under construction and is expected to be completed by 2032. Although the length of bridges and tunnels accounts for over 95% of the middle railway section, how to minimize impacts of snow avalanche hazards in this region is one of important scientific questions and engineering measures for this 21st-century mega project.

In this study, after an overview of the current status of snow avalanche research in Tibet, the spatial distribution characteristics and controlling factors of main snow avalanche hazards and casualties in Tibet are reviewed. Snow avalanche-prone areas in Tibet are then mapped based on the spatial distribution of snow cover and DEM (Digital Elevation Models) data, which are validated using field observations. The study aims to reveal the spatial distribution characteristics and temporal evolution of snow avalanches and related hazards in the mountain regions of Tibet, to further improve our understanding of snow avalanche hazards, and to provide scientific basis and support for decision-making to prevent avalanche hazards in high mountain region of Tibet.

2. Snow Avalanche Hazards

2.1. Overall Overview in Tibet

According to snow avalanche survey data in Tibet [37], a total of 110 snow avalanches (including ice avalanches) had occurred in Tibet from 2015 to 2019, resulting in 25 human deaths. They were spatially distributed in the Nyainqentanglha Mountain Range (47), the eastern Himalayas (27), and the central Himalayas on the Tibet side from Tingri to Nyalam counties (20), accounting for 85.5% of the total avalanche events in Tibet. In terms of regional distribution, the frequency was the highest in the Chamdo and Nyingtri prefectures in southeastern Tibet, with 39 and 37 avalanches recorded, respectively, followed by 16 in the Shigatse prefecture, while no avalanches were recorded in Lhasa area and only one event in the Ngari prefecture. In terms of county distribution, Nyalam County in the Shigatse prefecture, Metok and Bomi counties in the Nyingtri prefecture had the highest number of avalanches, with 22, 20 and 13, respectively. Among 110 events, there were specific dates for 65 avalanche occurrences, which shows that avalanche hazards mainly occurred in spring and winter. Avalanche hazards occurred in all months except from June to October and their frequencies increased per month from December and reached the highest of 31 events in March, accounting for 42.7% of the total numbers of events. According to this record, the number of avalanche hazards shows increasing trend in Tibet recently. Before 2016, the number of avalanche hazards was less than 10. Since 2017, more than 10 avalanche hazards have occurred in three consecutive years, and 52 occurred between 2017 and 2019, accounting for 80.0% of the total number of avalanche hazards.

In addition to the avalanche records above, some major avalanche hazards that occurred in Tibet have resulted in significant loss of life and property. On 3 January 1991, a snow and ice avalanche occurred on Mount Kawagarbu in southeastern TP, killing seventeen mountaineers. On 6 February 2013, six people died in a snow avalanche in Thada County, Ngari Prefecture. On 16 October 2013, an avalanche occurred in the mountainous area of Tingri County in Shigatse in southwestern Tibet, killing four people. On 17 July and 21 September 2016, Arutso glaciers No. 53 and No. 50 collapsed successively in Arutso basin, Rutok County, Ngari Prefecture, killing nine local herdsman. This was the first-ever recorded massive glacier collapse disaster in Tibet [38,39].

2.2. Avalanche Hazards in Southeastern Tibet and Himalayas

The southeastern Tibet receives plentiful snowfall during winter and spring seasons due to warm and humid airflow from the Indian Ocean. Along with high mountains and steep slopes in these regions, snow avalanches often occur and causes serious damages to local transportation, infrastructure, construction, and people's lives and properties. Snow avalanches and glaciations are prevalent near the snow line in southeastern Nyainqentanglha Mountain and eastern Himalayas. Snow avalanches near the big bend of Yarlung Zangbo River can transport ice and snow to subtropical valley at an altitude of 2400 m and form regenerated glaciers in some areas [29].

In addition to southeastern Tibet, the southern slope of Himalayas is rich in snowfall due to windward slope and orographic uplifting, which is very conducive to snow avalanches. On 17 January 2023, a catastrophic snow avalanche occurred at the exit of Duoxiongla Tunnel in eastern Himalayas and caused 28 people death, which is one of the deadliest avalanche-caused casualties in the history. However, it was not the only snow avalanche event in this region. As early as 1 April 2021, a snow avalanche hit at the exit of Doxiongla Tunnel, resulting in the death of four construction workers. In the southern slope of the central Himalayas, snow avalanches and blizzards often occur along Nyalam to the Friendship Bridge section of the China–Nepal highway in winter and spring, causing great hazards to transportation and people's lives and property in the region. Snow avalanches also occur in southern part of Kyirong, Purang, Tsada, and Tingri counties, resulting in casualties and damages [29]. In contrast, due to much flatter terrain condition and less precipitation in the interior plateau, the development of snow avalanches is greatly constrained. The only perennial snow avalanches can occur in snow-covered high mountains and glacierized areas.

2.3. Avalanche Hazards Along Sichuan–Tibet Highway Corridor

The research on snow avalanches and related prevention and control measures in Tibet were mostly motivated by the importance of the Sichuan–Tibet highway. Anjula to Tongmai section is an important part of the Sichuan–Tibet highway and the key section for mitigation and prevention of snow avalanches in the G318 national highway. This road section is located near the great bend of Yarlung Zangbo River in southeastern Tibet. The Parlung Zangbo River, as the largest tributary of Yarlung Zangbo River by volume, flows from east to west. With high mountains and deep valleys, various mountain hazards are very active along the road section due to specific geologic structure, landform, and hydrometeorological conditions. It is rare even in China in terms of the various types, high density, and frequency of mountain hazards [40]. Snow avalanche is among these mountain hazards in the region. Due to the influence of warm and humid airflow from the Bay of Bengal in the south, the precipitation in this region is very plentiful during the monsoon season. The mountains above the altitude of 5000 m are widely snow covered and marine type glaciers have developed [41]. Snow and ice avalanche actions near and above the snow line are very active [29]. Especially, in the Guxiang area between Bomi and Tongmai, snow avalanche accounts for 54% of glacier material supply and 6.4% of glacial water storage, where is the largest ice and avalanche action area in the TP [40].

In terms of casualties caused by snow avalanches, on 24 March 1996 a snow avalanche occurred in Ranwu Town, killing 56 people. On 24 March 2011, an avalanche occurred in Galongla Mountain, causing more than 10 people death or missing. On 3 April 2021, an avalanche occurred in Bagai Township in the basin, and all people passing through this area were evacuated in time and caused no casualties. The middle section of the Sichuan–Tibet Railway is under construction and traverses in this basin from east to west, and how to reduce the impact of avalanche hazards involves important scientific questions and engineering measures.

3. Materials and Methods

3.1. Study Area

The study area is Tibet, also referred to as the Tibet Autonomous Region (TAR), a province-level administrative region in China. Tibet is often used for the short name for TAR, located in the southwestern TP, while the TP is a vast region that covers most of high mountain regions in the western China, including all of the TAR and Qinghai province [42]. Tibet (TAR) is surrounded by the Himalayas in the south and southwest, the Karakoram in the northwest, the Kunlun Mountains in the north, and Tanggula Mountain in the northeast, and it is bounded by Jinsha River (Upper Yangtze River) in the east. The Gangdise and Nyainqentanglha Mountains traverse southern Tibet from west to east, while the valleys and rivers lie between these high mountains in the south and east [43]. The Sichuan—Tibet highway and railway pass through southeastern Tibet from Chengdu in the east to Lhasa in the west, as shown in Figure 1.

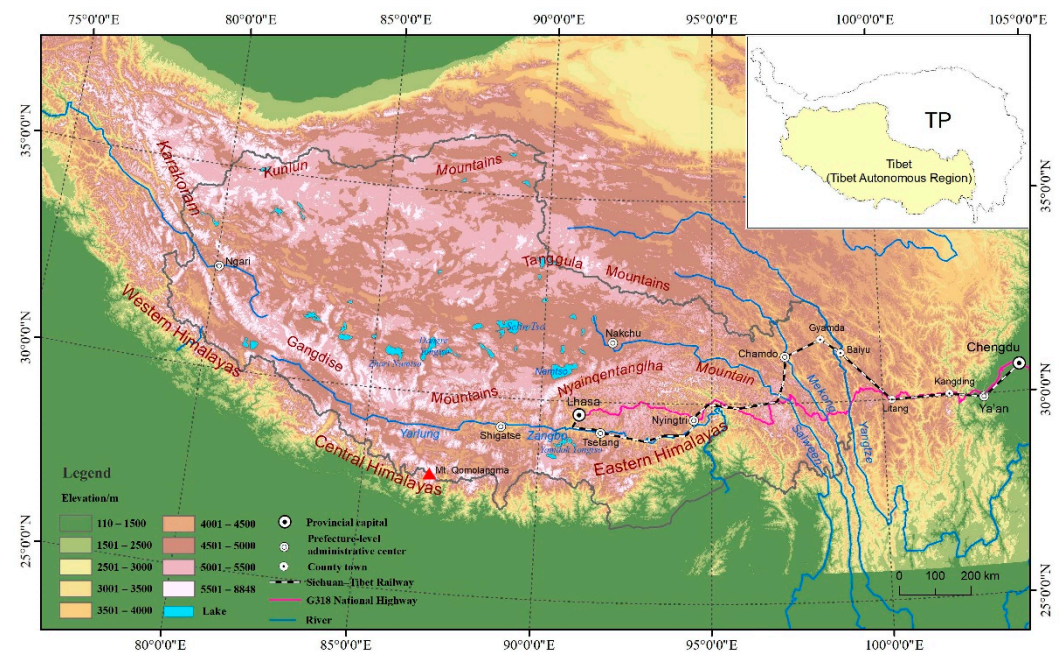


Figure 1. Study area.

3.2. Methods and Data

Determining snow avalanche-prone areas is essential to hazard prevention and mitigation in snow-covered mountain areas [35]. It will help decision-makers and planners to implement appropriate avalanche risk reduction strategies to reduce risk and prevent the loss of life and property [4,35]. Various methods are used for determining avalanche-prone zones, such as field investigations, GIS, remote sensing, and numerical modeling. Avalanche risk zoning and mapping criteria in the mountain regions, such as in Switzerland, were made based on the long-term field observation data recorded by the specialized Swiss Federal Institute for Snow and Avalanche Research (SLF) [44]. However, these methods cannot be directly applied to the TP area due to the lack of detailed long-term snow avalanche documentation [35,45,46].

It is well-known that snow avalanches are a type of serious natural disaster that commonly occur in snow-covered mountains with steep terrain characteristics [3]. It means that snow cover and mountain slope are the most important factors to drive snow avalanches in the mountain regions. The terrain is an essential factor and the only factor that is constant over time. The primary variable in avalanche terrain is a slope incline that allows avalanches to start and accelerate [47]. Slope inclination is the most important terrain parameter in mapping avalanche-prone areas, and the majority of snow avalanches in the mountain regions occur on slope gradients between 30° and 50° [48]. The slope angle > 30°

is usually required for dry snow slab avalanches, and the systematic identification of starting zones has been restricted to slope angles between 30° and 50°. The study also shows that a slope angle > 30° is topographic condition for snow avalanche occurrences in the mountain regions in the TP [49]. The optimal slope gradient for snow avalanches along the Sichuan—Tibet highway is 30–45° [49]. In the Himalayan range, about 90% of all avalanches begin on slopes of 30–45° [14,50]. Therefore, a slope angle > 30° is used in the mapping method, which is derived from SRTM (Shuttle Radar Topography Mission) DEM data that has been archived in the U.S. Geological Survey's Center for Earth Resources Observations and Science (USGS EROS). The original resolution of SRTM DEM is 90 m and is then resampled to 500 m to be consistent with MOD10A2 snow cover products.

To present the spatial distribution of snow cover in the study area, snow cover frequency (SCF) is defined as the percentage of number of snow-covered pixels in the total pixels for a certain time span (month, season or year) based on the MOD10A2 v005 time-series snow cover data [51]. The equation is as follow:

$$SCF = (Fs/Ft) \times 100\% \quad (1)$$

where *SCF* is the percentile frequency of snow cover; *Fs* is the total number of snow-covered pixels in MOD10A2 time-series data; *Ft* is total number of pixels in MOD10A2 time-series data. In this study, a novel mapping method for avalanche-prone areas is proposed based on the spatial distribution of snow cover and steepness of mountain slopes.

Based on the long-term research experiences and testing spatial distribution of annual mean SCF using 10% interval of SCF, the perennially snow cover area including glacierized areas can be effectively detected using $SCF \geq 60\%$ threshold. Therefore, $SCF \geq 60\%$ is used for the identification of perennially snow avalanche-prone areas. Likewise, due to lower temperature during the winter, a higher SCF is conducive to snow avalanche releasing and start. After testing using a 10% interval of SCF, a $SCF \geq 60\%$ is more realistic for snow avalanching during the winter. In spring, snowfall, snowfall days, and snow depth are the highest among four seasons in the TP [51]. However, the snow cover duration in spring becomes shorter and snow melts more quickly due to temperature rising. After testing the spring mean SCF, a $SCF \geq 30\%$ is more realistic for spring snow avalanching. Moreover, the elevation > 2000 m is used for mapping criteria due to very limited areas below 2000 m of elevation.

4. Snow Avalanche-Prone Area Mapping and Verification

4.1. Snow Cover

Annual mean snow cover in Tibet was mapped based on SCF derived from MODIS snow cover product from 2000 to 2015 using Equation (1) and is shown in Figure 2. Snow cover in the study area is unevenly distributed and generally presents that there is rich snow and more perennial snow cover with high SCF in the southeastern and surrounding high mountains, whereas there is less snow and low SCF in southern Tibetan valley and central part of northern Tibet. Snow cover in Tibet is highly associated with terrain features. The higher SCF corresponds well with the high mountain ranges. Annual mean snow cover is less than 4% below an altitude of 2000 m and reaches 75% above an altitude of 6000 m [42].

Winter and spring are the two seasons with the highest snow cover frequencies and snow-cover related cryospheric hazards in Tibet. Therefore, the mean snow cover in winter and spring was also mapped based on the same snow cover data and are shown in Figure 3. The spatial distribution of the snow cover in winter and spring is similar to the annual mean snow cover and generally shows that rich snow and high SCF on the interior and surrounding high mountain ranges, with less snow and low SCF in inland basins and river valleys (Figure 3). In the spring, the number of snowfall days in Tibet is the highest, accounting for 45% of the annual average, and the average snow depth is the highest as well. The highest snow depth is generally observed at stations in the southern slope of Himalayan Mountains.

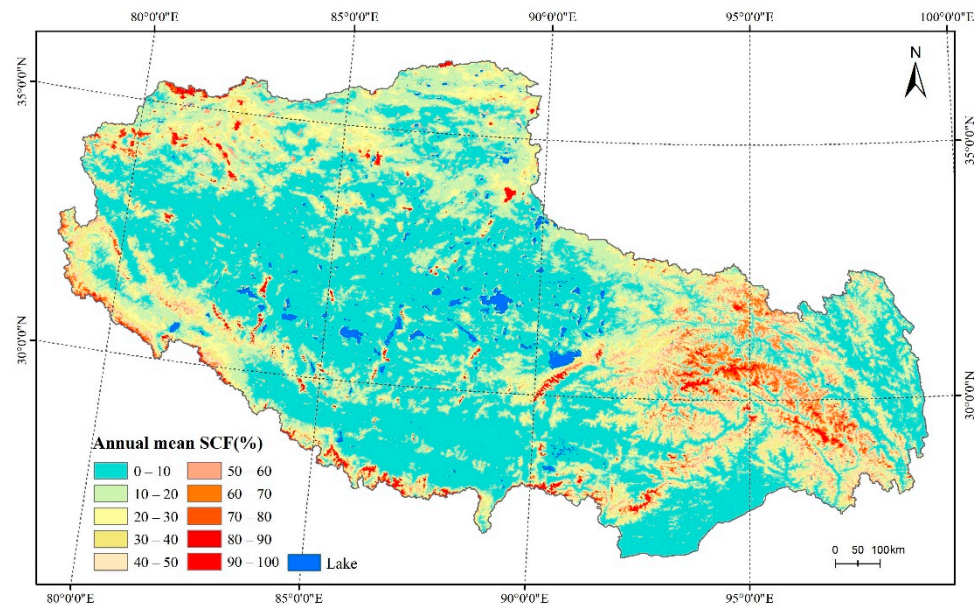


Figure 2. Annual mean SCF in Tibet.

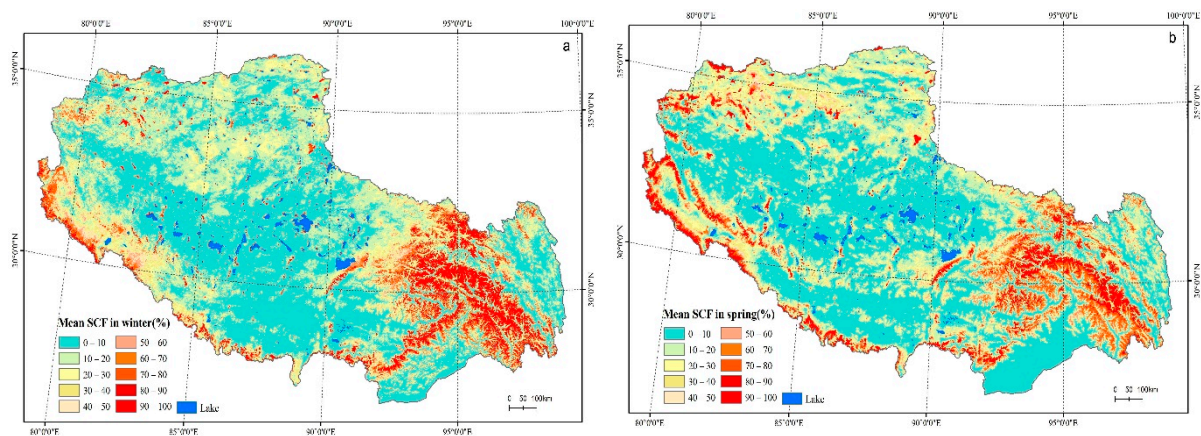


Figure 3. Mean SCF in winter (a) and spring (b) in Tibet.

4.2. Snow Avalanche-Prone Area Mapping

In addition to the importance of its water resources, snow cover plays a significant role in regulating climate through the snow albedo feedback in the TP and surroundings. However, excessive snow and snow cover often bring about snow-related hazards. Snow avalanches, as one of the cryospheric hazards in snow-covered mountain regions worldwide, are rapid gravity-driven mass movement of snow from the mountain slopes.

Mountain slope plays a critical role in the formation and occurrence of snow avalanches in snow-covered mountain areas. The analysis on the slope data derived from SRTM DEM shows that the topographic slope of most areas in Tibet is less than 30° , accounting for 88.6% of the total Tibet area. The area with a slope between 30° and 50° accounts for 11.2% of whole plateau area, while the area with a slope of more than 50° only accounts for 0.2% of the total area, which means that very steep mountains are quite limited in Tibet in spite of its massive mountain terrain. Although Tibet is known as the roof of the world and is a massive, elevated land mass on the Eurasia continent, the vast interior of the plateau is relatively flat.

According to mapping criteria of a slope gradient between 30° and 50° , $SCF \geq 60\%$, and elevation > 2000 m, the spatial distribution of perennial avalanche-prone areas in Tibet is shown in Figure 4. It presents that the perennial avalanche-prone areas in Tibet mainly lie in the Nyainqentanglha Mountains and its southeastern extension in the southeast and

Himalayan Mountains in the south. In the interior of the plateau, snow avalanches are likely to occur in steep terrain in glacierized and perennially snow-covered areas. The area of perennial avalanche-prone areas in Tibet is very limited, accounting for only 1.6% of the entire plateau area. Due to the limitations of snowfall and temperature conditions, snow avalanches in Tibet are highly seasonal, mainly occurring in spring and winter.

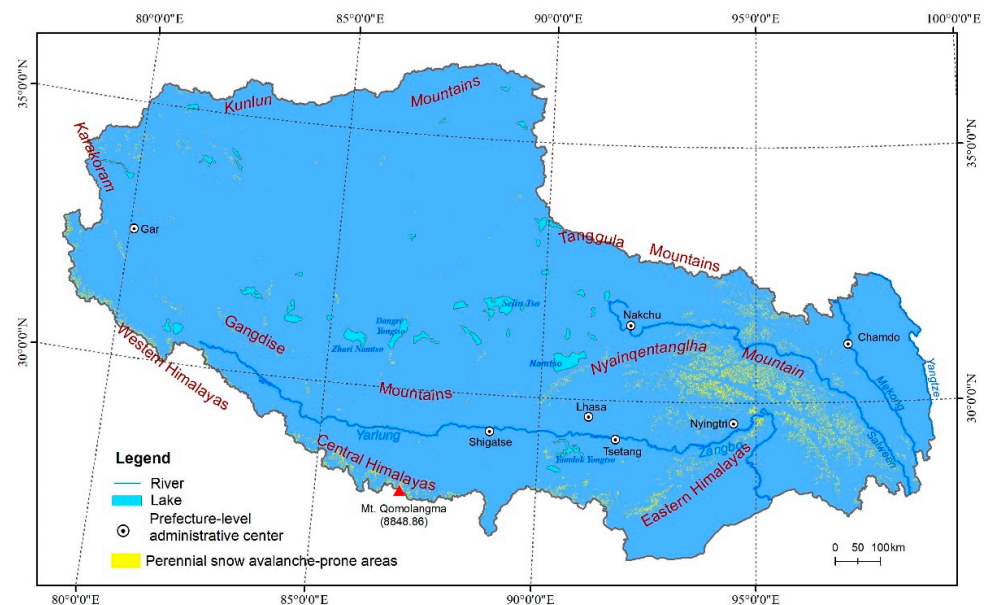


Figure 4. Perennial snow avalanche-prone areas in Tibet.

Based on the same method above, winter snow avalanche-prone areas in Tibet are shown in Figure 5. It is evident that winter avalanche-prone areas are mostly concentrated in the Nyainqentanglha Mountains in the southeast and the Himalayas in the south as well, while it is very limited in the interior of the plateau with relatively more in glacierized and perennial snow-covered areas in high mountains. Its spatial distribution is generally consistent with the distribution of perennial avalanche-prone areas, but its spatial distribution is obviously larger than that of perennial avalanche-prone areas, accounting for 2.9% of the total area of the plateau.

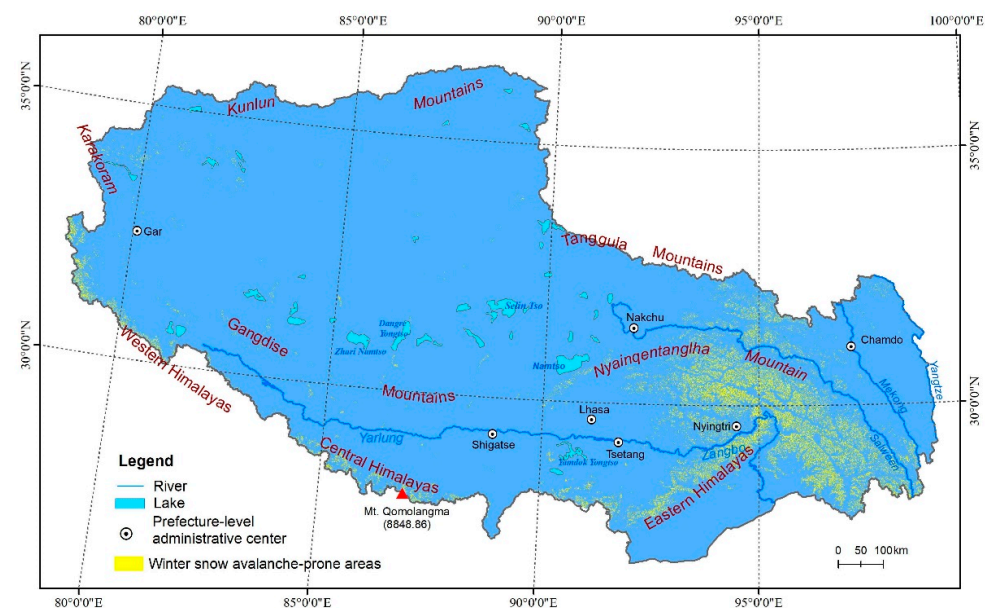


Figure 5. Winter snow avalanche-prone areas in Tibet.

Figure 6 shows the spatial distribution of spring avalanche-prone areas in Tibet. It can be seen that the spatial distribution of spring avalanche-prone areas in Tibet is generally similar with winter, but its spatial extent is obviously larger than that of winter, accounting for 4.1% of the total area, and the overall spatial distribution is also significantly more northward than that of winter. Spring avalanches are characterized by longer runout distances and reach lower elevations compared to winter avalanches [46].

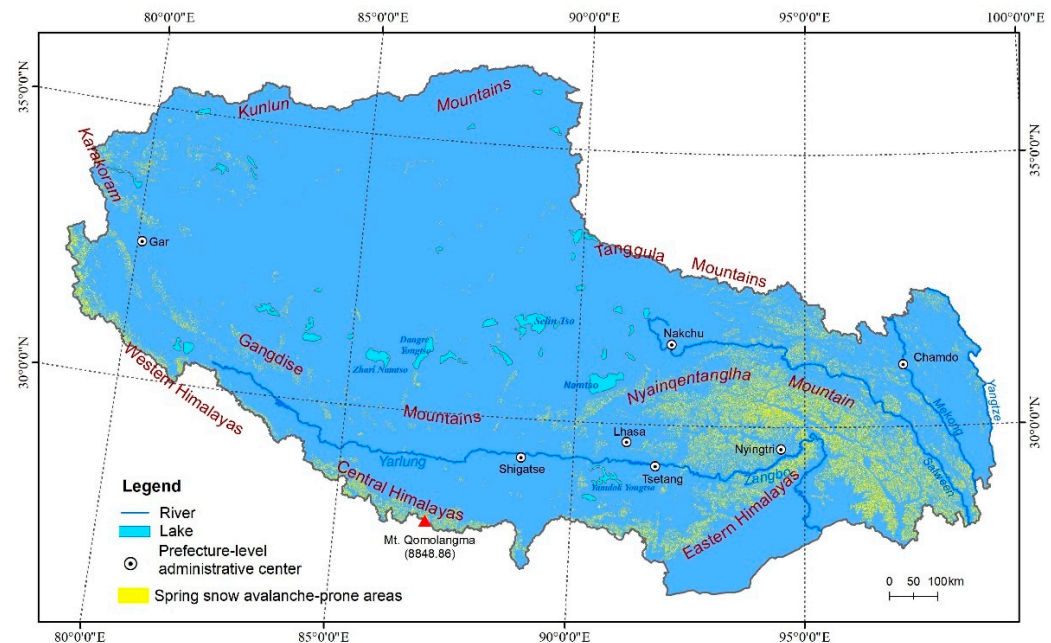


Figure 6. Spring snow avalanche-prone areas in Tibet.

4.3. Field Investigation and Verification

The field investigation on snow avalanches and snow cover was carried out along the G318 national highway, Zayul–Ranwu, and Zhamo–Metok highways from 6 April to 12 April 2023 after heavy snowfall in southeastern Tibet (Figure 7). A total of 22 avalanche deposition areas were observed on the roadsides. Among the 22 avalanche deposits, 13 were in the section from Bomi to Anjula along the G318, of which 8 were observed along road section between Songzong and Ranwu. The 7 avalanche debris fields were on the roadsides in the Zayul–Ranwu highway, but their scales were small with limited debris volumes. These small snow avalanches occurred on the opposite side of the highway and had no impact on the highway traffic. Two avalanche deposits were in the Galongla section of the Zhamo–Metok highway.

The field investigation shows that most of the avalanche deposits were in the mountain gorge region from Songzong to Ranwu towns in the Parlung Zangbo catchment with avalanching toward the north. Figure 7a is one of the typical channeled snow avalanches observed between Songzong to Ranwu towns. Figure 7b shows an avalanche bridge formed by an avalanche deposition, which is on the west side of the G318 Ranwu to Anjula section, and the river flows under the snow avalanche bridge. Snow avalanches run out eastward in order to adapt to the local terrain conditions. The investigation also shows that except for the Galongla section of the Zhamo–Metok highway, the impact of snow avalanches on the local road traffic is limited at present, but the destruction to slope forests and surface soil erosion is very serious. Especially, it is more obvious in the northern slope from Songzong to Yupu towns (Figure 7d) and the western slope of Guyu town (Figure 7e).

Four out of twenty-two snow avalanches caused road blockages, but they were cleared away and did not affect road traffic. Two out of four avalanche deposits and their moving channels were near the Langqiu village along the G318 national highway and are clearly visible in the Sentinel-2 satellite images on 15 April 2023, as shown Figure 8. The runout

distance of the first avalanche is 1.9 km and the second is 2.2 km. Satellite images show that there are many avalanche channels along the both sides of the valley at Langqiu village, but none of them have avalanched to roadsides except for the two snow avalanches mentioned above.

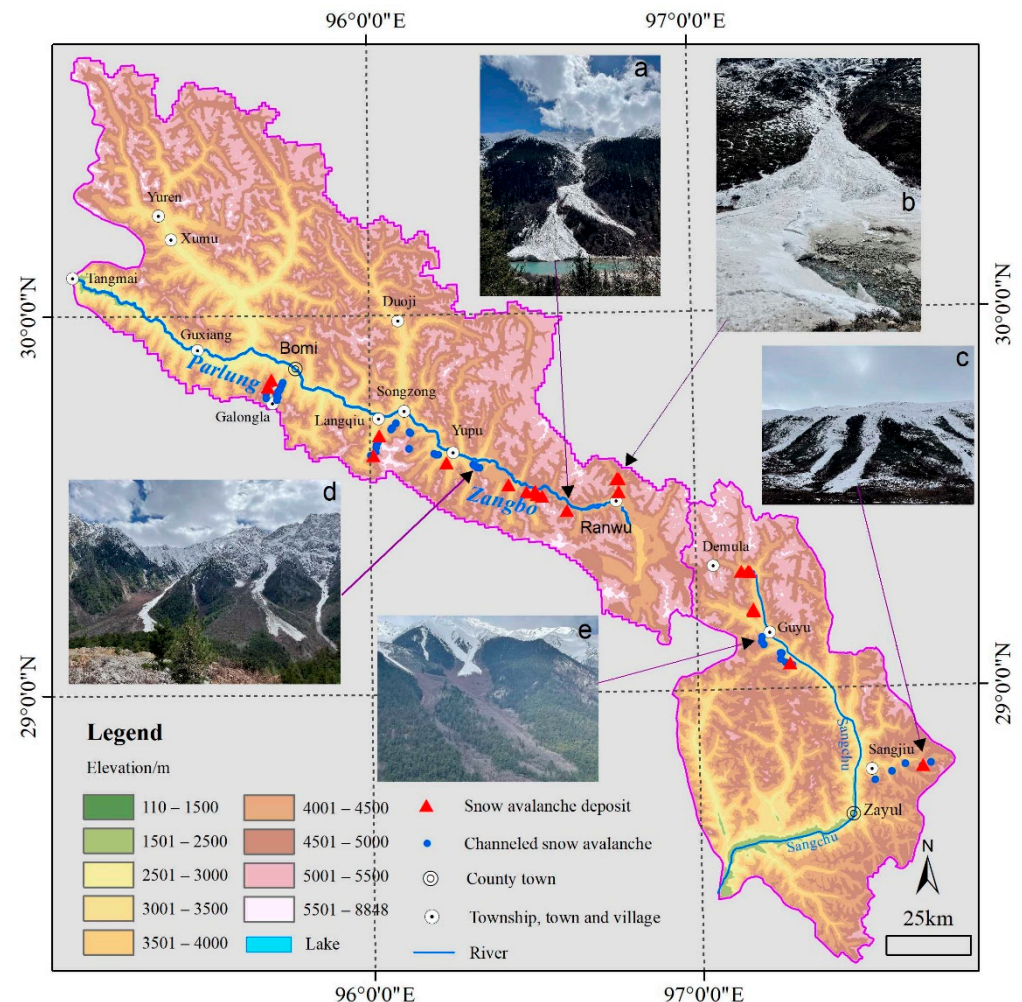


Figure 7. Field investigation on snow cover and snow avalanches in the Parlung Zangbo and Sangchu River basins. (a) A typical channeled snow avalanche; (b) snow avalanche bridge; (c) five channeled snow avalanches; (d,e) the destruction to forests on the mountain slope by snow avalanches.

Another two avalanche deposits were observed on the roadsides in the Galongla section from the Zhamo to Metok highway. They are also clearly visible in the Sentinel-2 satellite image on 23 May 2023, as shown in Figure 9. The runout distance of the first avalanche was 2 km and the second was 1.5 km. It can be seen from the Sentinel-2 satellite images that there are six large avalanche channels on the west side of the Galongla section, of which four have had a great impact on the local road traffic, including the two avalanche deposits mentioned above, while ten avalanche channels are on the east side of the highway, with one avalanche channel having a greater impact on the road traffic. Therefore, as the first high-resolution optical satellite data that are available to the public for free worldwide launched by ESA (European Space Agency), the Sentinel-2 satellite images can effectively detect snow avalanches in high mountain regions of Tibet.

Among the 22 avalanche deposits on the roadside observed during the field investigation, the shortest runout distance is 0.42 km and the longest runout distance is 2.2 km, with an average of 1.4 km. Most of the runout distances of snow avalanches are between 1.0 and 1.9 km, and snow avalanches mainly run northward. The lowest altitude of the starting point of snow avalanches is 3968 m, and the highest altitude is 4960 m, with an average of

4500 m or so. The lowest altitude of avalanche deposits is 3053 m, and the highest altitude is 4228 m, with a difference of 1175 m and an average of 3679 m. The elevation of avalanche deposits generally is higher in the east than in the west due to the east–west trending of the Parlung Zangbo catchment.

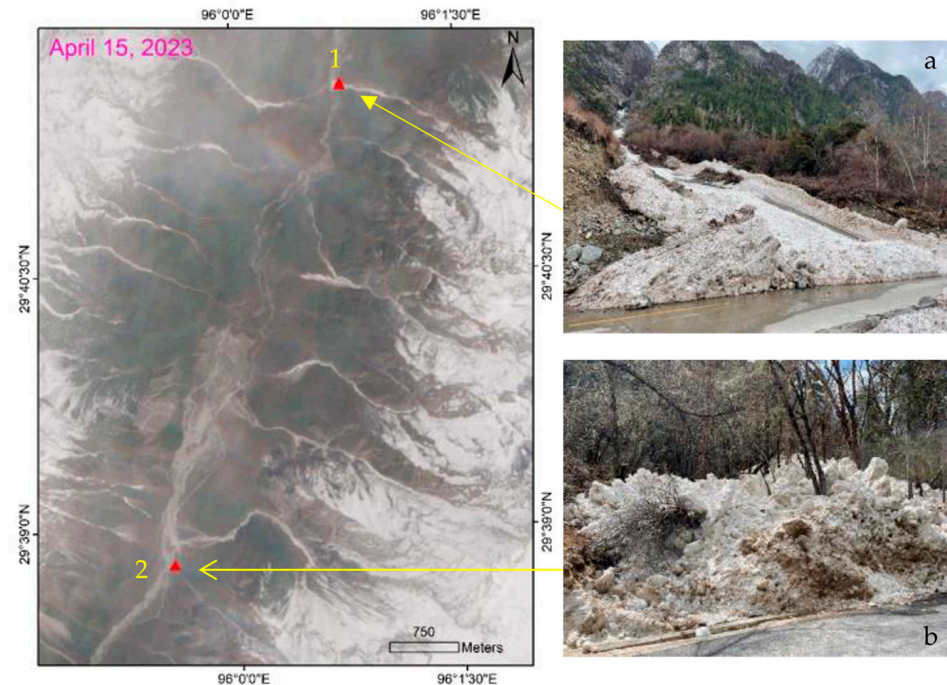


Figure 8. Snow avalanche deposits at near the Langqiu village in the Sentinel-2 image (left). (a) Avalanche deposit in the location 1 in the Sentinel-2 image; (b) avalanche deposit in the location 2 in the Sentinel-2 image.

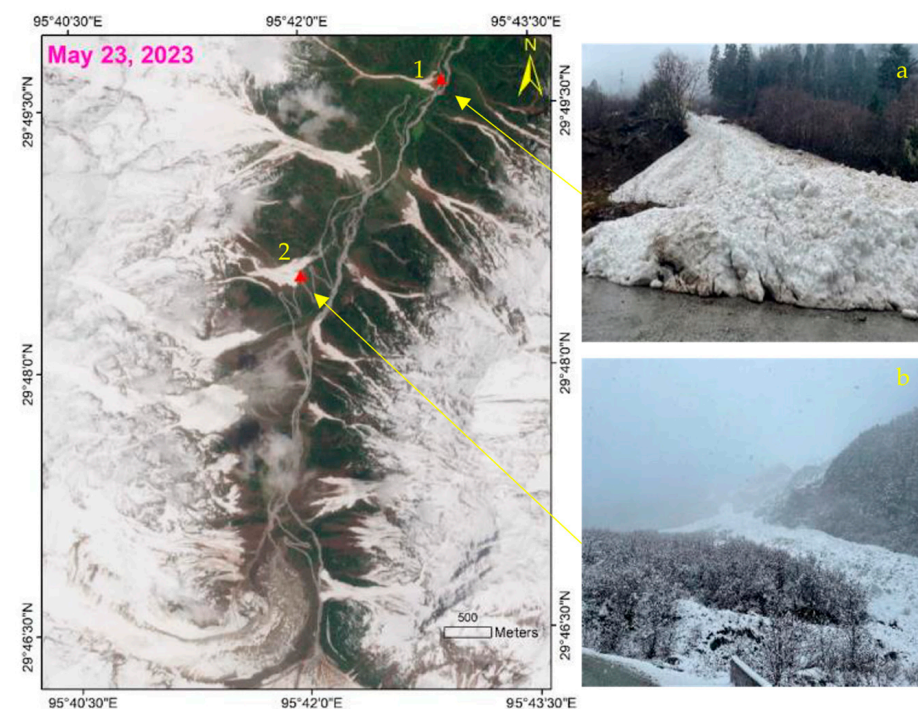


Figure 9. Snow avalanche deposits at Galongla section from Zhamo to Metok highway in the Sentinel-2 image (left). (a) Avalanche deposit in the location 1 in the Sentinel-2 image; (b) avalanche deposit in the location 2 in the Sentinel-2 image.

With observations during the field investigations, a total of 49 channeled snow avalanches were visually interpreted and identified from the cloud-free Sentinel-2 satellite images on 15 and 18 April 2023 as the closest cloud-free images found. Among these, 19 avalanches were in the Langqiu to Ranwu section as the most concentrated area, of which 12 were in the south of Songzong town with larger scales and volumes, followed by the Zayul–Ranwu highway section, with a total of 16 and most of them being around Guyu town. The 14 avalanche deposits were in the Zhamo–Metok highway section, with 10 on the east side of the road and 4 on the west side of the road. Except for the Galongla road section, these avalanche deposits are far away from the highway and currently have no hazard risks to road traffic in general, but due to larger scales and volumes the destruction to forests and surface erosion is considerably prominent. Among the 49 channeled snow avalanches visually interpreted from the Sentinel-2 satellite images, the shortest runout distance is 0.8 km and the longest runout distance is 2.8 km, with an average of 1.5 km and mainly running the north, which is consistent with previous findings [46]. The lowest elevation of the starting point is 3895 m and the highest elevation is 4839 m, with a difference of 944 m and an average is 4409 m. The lowest altitude of avalanche deposits is 3021 m and the highest altitude is 4116 m, with a difference of 1095 m and an average of 3457 m.

In addition to snow avalanches, snow cover on the roads is the main snow-related hazard that affects traffic in the high mountain regions in the cold seasons. During the field survey, the deepest snow cover on the road was measured at the Zhela Mountain Pass in Zayul County with over 2 m of snow depth, followed by the Demula Mountain Pass with over 50 cm and by the Sejila Mountain Pass with over 30 cm of snow depth. In southeastern Tibet, water vapor is abundant due to a southwesterly flow from the Bay of Bengal, which often brings heavy snowfall during snow season. Snow cover on the high mountain passes often causes snow hazards and affects road traffic in winter and spring seasons. The field investigation found that the highest frequency of snow avalanche along the G318 highway occurred from Songzong town to Ranwu Lake. Although the Galongla Tunnel was constructed in 2010, the Galongla section of the Zhamo–Metok highway is still a pivotal area to prevent snow and avalanche hazards in southeastern Tibet.

According to the 22 avalanche deposits found during the field investigation, combined with Google Earth high-resolution satellite images, the starting point, runout distance and deposition location of these channeled snow avalanches were identified using the cloud-free Sentinel-2 satellite images acquired on 15 and 18 April 2023. On this basis, the overall accuracy of spring avalanche-prone areas was validated by using the starting points of 22 avalanches as reference values. The results showed that overall accuracy of spring snow avalanche-prone areas reached 77.3%, with 5 avalanches missed out of a total of 22. This accuracy is generally acceptable for snow avalanche-prone area mapping for mountain regions of Tibet with complex terrain and high altitude. The reason for missing 22.7% of avalanches is that the snow cover (SCF) of the starting points of observed snow avalanches is less than 30% or the slope gradient of the starting points of observed snow avalanches is less than 30°. Finally, the five avalanches occurred outside the avalanche-prone areas.

4.4. Snow Avalanche-Prone Areas in the Parlung Zangbo and Sangchu River Basins

In southeastern Tibet, the highest frequency of snow avalanches and the most extensive snow avalanche-prone areas are in the Parlung Zangbo and Sangchu River basins [29]. To present the spatial details of the snow avalanche-prone areas, the perennial and seasonal snow avalanche-prone areas in the basins were extracted from Figures 4–6 and are shown in Figures 10–12, respectively.

The perennial snow avalanches generally occur in the high mountains and glacierized areas at altitude above 4500 m in summer or all year round. In the high mountain glacierized areas, snow avalanches are common around cirque basin and behind the headwalls. Around cirque basin, snow is difficult to accumulate due to steep mountain slopes and avalanches to the cirque basin [29]. Seasonal snow avalanches generally occur in the middle and high

mountains with proper temperature and abundant solid precipitation, and they mainly occur in spring and winter.

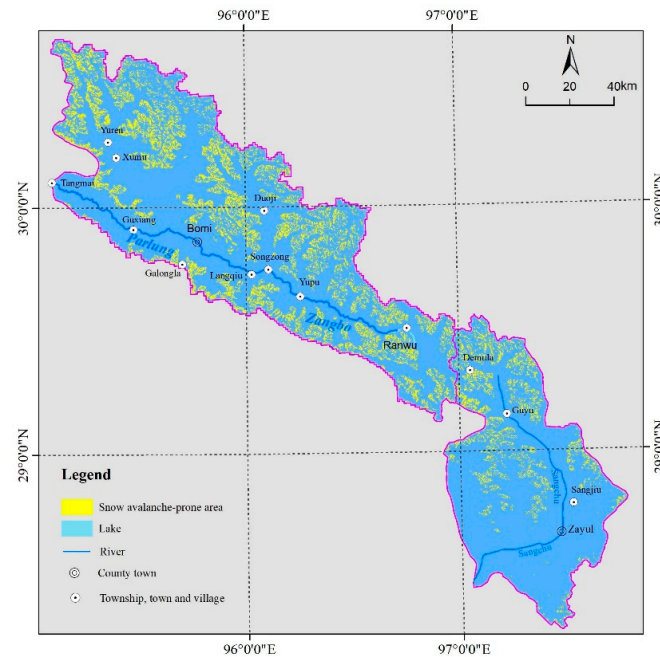


Figure 10. Perennial snow avalanche-prone area in the Parlung Zangbo and Sangchu River basins in southeastern Tibet.

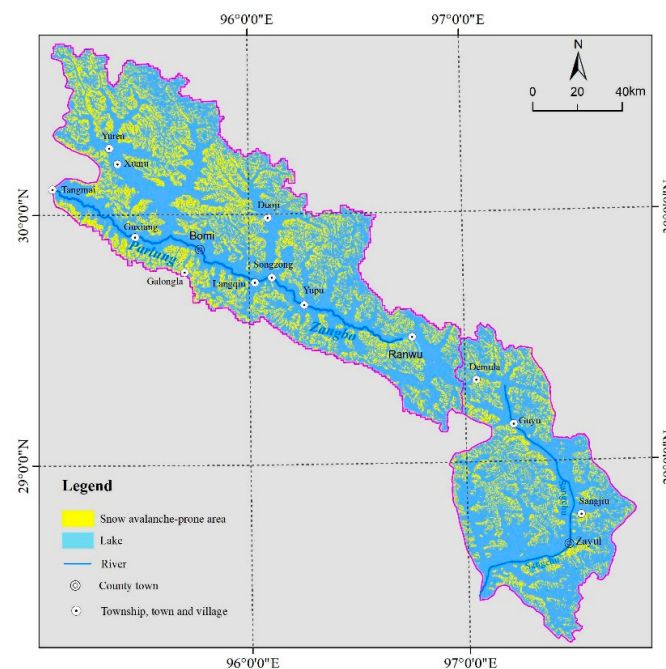


Figure 11. Snow avalanche-prone areas in winter in the Parlung Zangbo and Sangchu River basins in southeastern Tibet.

As shown in Figure 10, perennial avalanche-prone areas in the basin are mainly in the alpine perennial snow-covered areas on both sides of the valley and are more widely distributed in the alpine mountains with higher altitude and latitude on the north side of Parlung Zangbo River, while there are no perennial avalanche-prone areas distributed in the lower reaches of Sangchu River in the south. Summer is the raining season in the plateau. Most of the glaciers in the interior plateau are mainly fed by summer precipitation,

so that snow–ice avalanches are frequent all year round in the glacierized areas, which become important material sources for maintenance and development of glacier mass.

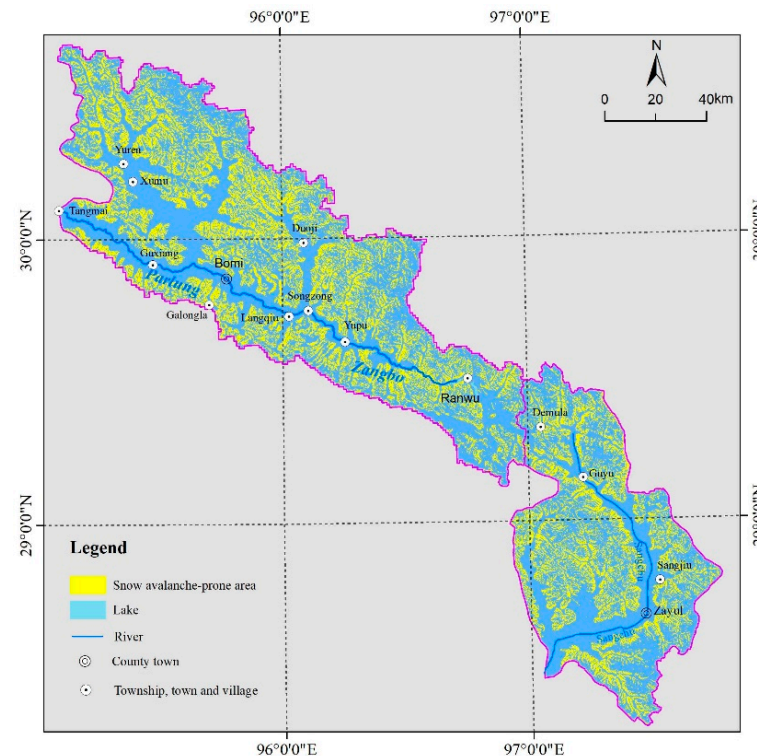


Figure 12. Snow avalanche-prone areas in spring in the Parlung Zangbo and Sangchu River basins in southeastern Tibet.

Figures 11 and 12 show the winter and spring snow avalanche-prone areas in the Parlung Zangpo and Sangchu River basins, accounting for 23.8% and 30.7% of total areas of two basins, respectively. Most of the high mountain regions on both sides of the valley are prone for snow avalanche during spring and winter. The spatial distribution of avalanche-prone areas in winter and spring is similar, but avalanche-prone areas in winter and spring is obviously larger than perennial avalanche-prone areas. Especially, this difference is more distinct in the spring.

Parlung Zangpo and Sangchu River basins are located on the passage of the southwest monsoon that brings warm and humid airflow into the plateau, which is most affected by the southwest monsoon and is the region with the longest duration of southwest monsoon influence in Tibet. Snowfall during winter and spring is very conducive to the development of ice and snow avalanches in the region. Particularly, during the spring, when temperature rises rapidly from March to April, the snow melts quickly and meltwater penetrates into snowpack layer, causing snow layer breaking and avalanching, which can easily result in avalanche disasters.

In the spring, the largest snowfall and highest snow avalanches occur in southeastern Tibet, with monthly highest snow avalanches occurring in April. The main differences between perennial and seasonal snow avalanches are that the former contains many white ice blocks with about 20–50 cm long, while seasonal snow avalanche has no ice blocks [29]. As an important part of the G318 Sichuan–Tibet highway, the Anjula–Tongmai section is located near the big bend of Yarlung Zangbo River in southeastern Tibet and passes through the high mountains and deep gorge areas in the Parlung Zangbo River basin. Various mountain hazards along the highway are very active and snow avalanche is one of these mountain hazards. The Sichuan–Tibet Railway under construction traverses the Parlung Zangbo River basin from east to west (Figure 1). The identification of snow avalanche-

prone areas has important guiding significance for safety operation for the Sichuan–Tibet highway and railway.

5. Discussions

Snow avalanches are a well-known hazard type in the mountain regions and are defined as a sudden release of snow masses and ice from the mountain slopes [25]. They damage lives, property, infrastructure and terrestrial ecosystems, and thus are considered “white death” in glacier regions [3,26]. Snow avalanche research and relevant prevention and control measures in Tibet area are mainly driven by the safety operation of the Sichuan–Tibet highway in the past, and the potential impact on the Sichuan–Tibet railway that is under construction.

A comprehensive review for snow avalanche hazards and major casualties in Tibetan history over the last 50 years was made in the study. There are reports about fatalities caused by snow avalanche hazards almost every year, and this trend is increasing due to global climate warming. The limited record shows that there is an increasing trend in the number of snow avalanche hazards and casualties in Tibet recently, most likely due to more human activities at high-altitude regions and documentation. In the Tibet area, before 2016 the number of avalanche hazards was less than 10, while it was more than 10 in recent years. The same increasing trends were found at high-altitude regions in the central and western Himalayas [14,52]. In addition, increased warming has enhanced the frequency and intensity of extreme precipitation events and has accelerated the ice and snow melting, which brings a significant increase in avalanche events [35,52,53].

Mapping snow avalanche-prone areas is particularly important for hazard risk mitigation and prevention in the mountain regions. Snow avalanche-prone areas in Tibet were mapped based on the spatial distribution of snow cover and mountain slopes, and the result was validated against in situ observational data. A clear picture of spatial distribution of snow avalanche-prone areas in the Tibet area with adequate accuracy was given in the study, and it was found that the highest frequencies of avalanche occurrences are in the southeastern Nyainqentanglha Mountains and southern slope of Himalayas, which is consistent with previous study [29]. Moreover, in this study the quantitative analysis was given for snow avalanche-prone areas in the plateau compared to previous qualitative description. More specifically, the highest frequencies of snow avalanches and most extensive snow avalanche-prone areas were in the Parlung Zangbo River basin in southeastern Tibet. The snow avalanche susceptibility map shows that the high snow avalanche-prone areas are mainly distributed in the upper narrow valley section of the Parlung Zangbo catchment along the G318 national road and mountain ridges on both sides of the middle and lower reaches [35].

6. Limitations and Outlook

A novel mapping method for avalanche-prone areas was proposed based on snow cover and DEM data and was validated against ground observations. The overall accuracy of the methods in spring reaches 77.3%. This accuracy is generally acceptable for snow avalanche-prone area mapping for mountain regions with complex terrain and high altitude in Tibet. The advantage of methods compared to other methods is to require only two key parameters for mapping snow avalanche-prone areas [4,35].

However, snow avalanches are complex processes that are driven by snowfall, snow cover, mountain slope, air temperature, wind speed, terrain roughness, land cover, and many external forces, and they are caused by snowpack instability [48]. In addition to snow cover and mountain slopes, snowfall is the most important parameter to trigger avalanches and largely determine avalanche scale and danger [20,21]. The method of forecasting snowfall-triggered avalanches can overcome the difficulties of snowpack stability tests to warn of a regional avalanche [21,22]. Snowfall threshold and meteorological conditions of snow avalanche occurrence varies in different regions due to the difference in climate and snow characteristics [19,20]. Snow avalanche release is often spontaneous and is sometimes

caused by external factors, such as earthquakes, humans, or animals. The timing and frequency of snow avalanches are intricately linked to factors such as snowfall intensity, periods of intense winds, or sudden fluctuations in air temperature over short durations. Extreme weather such as cyclonic storms and blizzard can bring anomalous snowfall over a very short period, leading to unstable snow cover and a high risk of snow avalanches during and after the storms [22,53]. Therefore, mapping methods can be improved in the future with more meteorological and topographical parameters involved.

In addition, the Tianshan Station for Snow Cover and Avalanche Research (TSSAR) established in 1967 is the only spatialized research institute in China [19]. In the TP, there have been no specialized institutions for avalanche monitoring and research, resulting in a lack of long-term avalanche records and documentations. Therefore, it is not possible to build mapping criteria and make accuracy assessment for snow avalanche-prone areas using historical records currently. However, remote sensing technology allows objective, reliable, and spatially continuous measurements of avalanche activity at various spatial dimensions. Particularly, high-resolution optical images from Sentinel-2 and SPOT-6 and long-term historical data from Landsat series provide substantial reliability and extensive data for identifying snow avalanches, providing data support for long-term historical avalanche reconstruction, which can fill the gap of avalanche records and documentations in the TP to make mountain regions safer.

7. Conclusions and Recommendations

Snow avalanches in the mountain regions often bring serious loss of life and property. However, the current research on snow avalanche and related hazards in Tibet is inadequate compared to other cryospheric components and natural hazards, and the monitoring, early warning, and forecasting services are far from meeting the needs of current mountaineering, adventure tourism, and road traffic safety. The purpose of this study is to fill this gap and improve our understanding of snow avalanches and relevant hazards in Tibet and provide scientific evidence and support for prevention of avalanche hazards, which has significant implications for other global high mountain areas. Main conclusions and recommendations are as follows:

- (1) Nyainqentanglha Mountain and its southeastward extension in southeastern Tibet and the southern slope of the Himalaya Mountains are two regions with the highest frequency of avalanches in Tibet. Snow avalanche is one of most dangerous natural hazards to road traffic safety in mountainous areas of Tibet during snow seasons. Of those, the Anjula–Tongmai section of the Sichuan–Tibet highway and Galongla section of the Zhamo–Metok highway are the most affected areas by snow avalanche hazards in the spring and winter seasons.
- (2) A mapping method for avalanche-prone areas was proposed based on snow cover and DEM data and was verified using ground observations. Overall accuracy of mapping method reached 77.3%. The perennial snow avalanche-prone areas accounted for 1.6%, while snow avalanche-prone areas in winter and spring accounted for 2.9% and 4.9% of the total area, respectively.
- (3) In recent years, human activities, such as mountaineering and adventure tourism, have become more frequent in the high mountains, and casualties and economic losses caused by snow avalanches show an increasing trend. Therefore, in addition to the implementation of engineering prevention and control measures in the key areas, such as in the Sichuan–Tibet highway and railway sections, monitoring, early warning, and forecasting services and related scientific research should be strengthened on the basis of detailed investigation and avalanche hazard zoning.
- (4) Enhancing popular science education on hazard prevention and reduction among the public and raising their awareness of disaster prevention is essential to prevent and mitigate avalanche hazards for the long haul. It is particularly important to promote science education on prevention of snow and ice avalanche hazards for mountaineers and adventure tourists.

- (5) Apart from snow avalanches, snow cover on the roads is the main snow-related hazard currently that affects traffic in the high mountain regions in Tibet during the cold seasons. Therefore, the study also suggested that, in addition to implementing engineering measures such as snow nets, shed holes and tunnels in the pivotal roads, enhancing monitoring, forecasting, and early warning services is crucial to prevent and mitigate relevant hazards in the Tibetan high mountain regions in the future.

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