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Estimation of snow load and avalanche hazard assessment in Southeastern Afghanistan through remote sensing techniques

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Abstract
The estimation of snow load is vital for hazard assessment and disaster risk management in Southeastern Afghanistan, a region distinguished by its high-elevation mountainous terrain and a high incidence of snow avalanches. Due to the limited availability of ground-based observations, remote sensing techniques have been widely utilized to analyze snow cover, avalanche frequency, and climatic trends. The Snow Avalanche Frequency Estimation (SAFE) model, which employs Landsat satellite data, to emphasize remote sensing's role in assessing climatic has successfully mapped zones susceptible to avalanches over a span of 32 years. Recent advancements in multispectral and passive microwave remote sensing technologies have significantly enhanced the evaluation of snow-covered areas and snow water equivalent (SWE), thereby facilitating flood prediction and effective water resource management. Climate change has intensified fluctuations in snowfall patterns, and consequently elevating the risks associated with snow-related hazards. This study explores various methodologies for estimating ground snow load, including empirical models, remote sensing applications, and machine learning approaches. Furthermore, it examines risk assessment frameworks and mapping techniques aimed at improving disaster preparedness. The findings underscore the necessity for region-specific modeling strategies and enhanced data collection methods to tackle the challenges presented by climatic variability. Future research should prioritize the integration of advanced geospatial technologies with in-situ measurements to improve the accuracy of snow hazard predictions in the complex mountainous landscapes of Afghanistan.

Keywords: *Estimation of snow load, remote sensing applications, impacts of climate change, risk assessment of snow avalanches, GIS-based hazard mapping, Southeastern Afghanistan.*

Introduction

The estimation of snow load is essential for conducting hazard assessments in Southeastern Afghanistan, primarily due to the frequent occurrence of snow avalanches in high-elevation mountainous regions. In response to the scarcity of ground-based observations within this data-deficient area, remote sensing techniques have been developed. The Snow Avalanche Frequency Estimation (SAFE) model, which utilizes Landsat satellite data, has effectively mapped avalanche frequency and identified as being within Afghanistan over a span of 32 years (Caiserman et al. al., 2022). Since 2004, annual snow assessments employing multispectral and passive microwave remote sensing have yielded valuable insights into snow-covered areas and snow water equivalent within major watersheds (Daly et al., 2012). These assessments are vital for understanding current snow conditions and assessing potential flood risks.

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The application of remote sensing techniques addresses snow avalanche hazard assessment critical data gaps prevalent in the inaccessible regions of Afghanistan. Southeastern Afghanistan is characterized by intricate topography and challenging climatic conditions. The region encompasses vast desert plains, towering mountain ranges, including the Hindu Kush, and scattered fertile valleys adjacent to significant rivers (Uhl, 2006). The climate is predominantly arid, featu-ring cold, snowy winters and hot, dry summers (Delmonaco and Margottini, 2014). Provinces in this southeastern region, such as Logar, Khost, Paktika, Paktia, Ghazni, and Wardak, encounter particular challenges exacerbated by ongoing conflicts, limited governmental authority, and complex physical geography (Groninger and Lasko, 2011). Water resources are vital for agricultural practices, with both surface and groundwater utilized for irrigation purposes (Uhl, 2006). However, improper land-use practices, overgrazing, and recurrent droughts have contributed to desertification in numerous areas, particularly in the southwestern plains (Hassanyar, 1977). Restoration initiatives must tackle these challenges and develop comprehensive revegetation plans that consider vegetation cover, soil characteristics, topography, and climatic conditions (Hassanyar, 1977). These studies underscore the pivotal role of infrastructure in disaster management and regional development. The establish-ment of adequate infrastructure across transportation, telecommunications, energy, and water sectors is impe-rative for facilitating global trade and attracting invest-ment (Ratnayake and Sarkar, 2006).

Transportation infra-structure, in particular, is crucial for the functio-ning of transport systems and necessitates thorough post-disaster impact assessments to ensure effective repair and reconstruction efforts (Gajanayake et al., 2020). The Hindu Kush Himalaya region, which encompasses parts of Afghanistan, is highly susceptible to various natural hazards due to its distinctive geographical and geological features (Vaidya et al., 2019). The effects of climate change further exacerbate the vulnerabilities faced by geotechnical infrastructure, especially in transportation and flood defense systems, potentially resulting in significant disruptions and safety concerns (Vardon, 2015). Collectively, these studies highlight the importance of fostering regional cooperation, enhancing disaster risk reduction strate-gies, and building resilient infrastructure, particularly in hazard-prone areas such as Southeastern Afghanistan.

Climatological factors affecting ground snow load

The estimation of ground snow load in southeastern Afghanistan is significantly influenced by a variety of climatological factors. The deployment of remote sensing techniques, including multispectral and passive microwave technologies, plays a crucial role in assessing snow conditions, particularly in areas where ground-based observations are limited (Daly et al., 2012). These methodologies facilitate the evaluation of snow-covered areas, measurement of snow water equivalent, and assessment of potential flooding risks. By integrating local climatological data, such as snow depth and daily temperature, with information obtained from first-order weather stations, it is possible to estimate ground snow loads more accurately (Fridley et al., 1994). Afghanistan's mountainous terrain experiences cold, snowy winters paired with hot, dry summers, and the wet season typically spans from winter to early spring (Delmonaco & Margottini, 2014). Seasonal snow cover mapping utilizing satellite imagery has illuminated the influence of the Indian monsoon on snow distribution patterns and has contributed to the assessment of avalanche hazards within the region (Kravtsova, 1990).

Influence of temperature, wind, humidity, and precipitation

Recent studies investigating climate change in Afghanistan have identified significant trends in temperature and precipitation across various regions, including Kandahar and mountainous areas. These investigations indicate that temperatures are exhibitting an upward trend, with minimum temperatures rising at a rate more rapid than that of maximum temperatures (Mujtaba et al., 2022; Aliyar, 2024). Precipitation patterns are heterogeneous; some regions are experiencing increases while others are seeing decreases (Rehana et al., 2021). Specifically, the northern, northeastern, and western zones are particularly vulnerable, facing reductions in precipitation alongside rising temperatures, which suggests the emergence of drier and warmer periods (Rehana et al., 2021). Such climatic changes present substantial challenges to Afghanistan's agriculture, water resources, and plant biodiversity (Mohammadi et al., 2024). The country's subtropical characteristics render it especially susceptible to the adverse impacts of clima-

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te change, including severe droughts, floods, and water scarcity (Mohammadi et al., 2024). These findings emphasize the necessity for comprehensive strategies to mitigate and adapt to climate change in Afghanistan.

Seasonal and regional variations in snowfall accumulation

Research on snowfall accumulation in southeastern Afghanistan reveals notable seasonal and regional variations. Since the 2004-2005 period, multispectral and passive microwave remote sensing techniques have been employed to assess snow conditions in major watersheds (Daly et al., 2012). Analysis indicates a decreasing trend in annual average snow cover in basins influenced by westerlies, whereas basins affected by the monsoon exhibit increasing trends, with seasonal fluctuations observed across varying topographic parameters (Hasson et al., 2012). Additionally, the influence of the Indian monsoon on snow cover distribution has been documented (Kravtsova, 1990). Recent research utilizing Sentinel-1 synthetic aperture radar (SAR) data and Differential Interferometric Synthetic Aperture Radar (DInSAR) techniques has facilitated the estimation of snow depth in the Hindu Kush Himalayas during peak winter and early melt seasons, showing good correlation with field measurements (Mahmoodzada et al., 2020). These findings underscore the significance of snow cover dynamics in regulating water resources for Middle Eastern countries and suggest the potential for seasonal streamflow forecasting in the region (Hasson et al., 2012). Table 1 presents a comprehensive overview of snowfall accumulation across various regions, indica-ting that the Hindu Kush experiences the highest levels of snowfall, which accounts for 55% of the region's water resources.

Table 1. *Regional variations in snowfall accumulation of different region Afghanistan*

Region	Annual Snowfall (cm)	Snowmelt Contribution to Water (%)	References
Hindu Kush	300	55	Daly et al. (2012) and Hasson et al. (2012)
Panjshir Basin	250	60	
North-East	180	40	
South-West	120	30	

Impact of climate change on snow load trends

Climate change is expected to have profound effects on snow cover and water resources in Afghanistan and the Western Himalaya region. Research indicates a significant decline in annual snow cover area (SCA) and river flow within the Panjshir basin by the mid to late 21st century (Azizi & Asaoka, 2020; Nepal et al., 2021). Projections estimate a reduction in annual SCA ranging from 10% to 36%, with more pronounced decreases observed during the autumn and spring seasons (Nepal et al., 2021). These alterations are likely to disrupt water-dependent sectors and endanger food security in the region (Mazloum Yar and Zarghani, 2024). The application of remote sensing technologies has proven essential for evaluating snow conditions in Afghanistan's primary watersheds. Such technologies facilitate the assessment of snow-covered areas, snow water equivalent, and potential flooding risks (Daly et al., 2012). The anticipated changes in the timing and availability of seasonal snowmelt, coupled with the overall decline in snow resources, underscore the urgent need for adaptive water management strategies in Afghanistan and its neighboring regions (Nepal et al., 2021; Mazloum Yar & Zarghani, 2024). Figure 1 depicts the annual decrease in snow cover from 2000 to 2020, illustrating the significant decline attributed to the impacts of climate change.

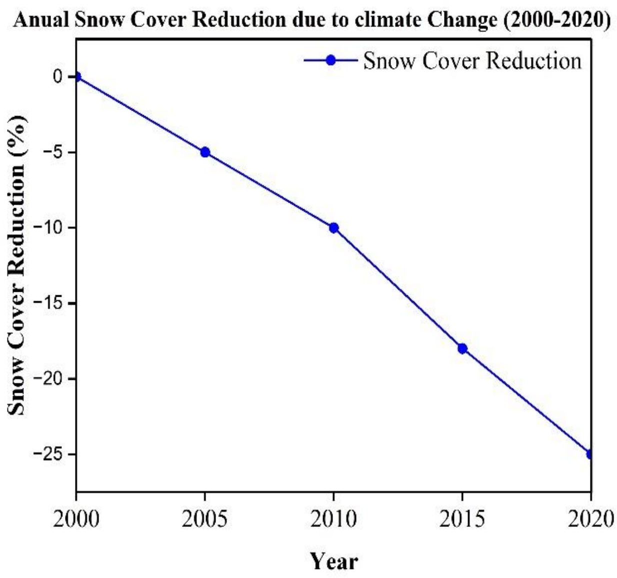

Figure 1. *Annual snow cover reduction due to climate change (2000-2020) (Nepal et al., 2021; Azizi and Asaoka, 2020.*

Methods for Estimating Ground Snow Load

Recent research has investigated various methodologies for estimating ground refers to the weight of accumulated snow and snow depth in Afghanistan, specifically within the Hindu Kush Himalayas region. Fridley et al. (1994) introduced a technique that employs local cli-

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matological data to estimate ground snow loads, establishing a relationship between water-equivalent depth, snow depth, and daily temperature. Expanded on the SAR/DInSAR method used by Mahmoodzada et al. (2020). Furthermore, remote sensing technologies have proven to be instrumental in assessing snow conditions across Afghanistan's major watersheds, with multispectral and passive microwave data offering valuable insights into snow-covered areas and snow water equivalent (Daly et al., 2012). In a significant contribution, Mahmoodzada et al. (2020) utilized Sentinel-1 SAR data in conjunction with a DInSAR-based framework to estimate snow depth in the Khanabad watershed during the peak winter and early melt seasons. Their findings demonstrated a strong correlation with field measurements. To mitigate the challenges posed by cloud cover in MODIS snow cover products, Gafurov and Bárdossy (2009) developed a six-step methodology designed to estimate pixel coverage in cloud-obscured areas, exhibiting high accuracy rates within the Kokcha River basin in northeastern Afghanistan.

Empirical models

This study addresses water management and streamflow characteristics in Afghanistan, emphasizing the challenges faced in agricultural development and hydrological assessments. In southeastern Afghanistan, ongoing conflicts, drought conditions, and social instability have significantly hindered effective land management and agricultural production systems (Groninger and Lasko, 2011). insights into the region's hydrological patterns (Olson & Sether, 2010). These analyzes encompass monthly and annual flow durations, probabilities of high and low discharges, and records of peak discharges. The studies underscore the necessity of understanding streamflow characteristics for effective water resource planning within Afghanistan's arid and mountainous environments, which are characterized by significant fluctuations in streamflow (Olson & Williams-Sether, 2010; Vining, 2010; Sahaar, 2013).

Remote sensing and GIS applications

Remote sensing and Geographic Information System (GIS) applications have demonstrated significant value in the realms of environmental monitoring and resource management in southeastern Afghanistan. An analysis of satellite imagery has indicated notable changes in forest cover within Paktia Province from 1998 to 2018, highlighting increases in both closed and open forest areas (Ariez et al., 2022). These technologies have also been effectively utilized to evaluate and prioritize projects aimed at improving water resources, incorporating various factors such as sedimentation, storage efficiency, and environmental impacts (Shovic et al., 2010). In the Helmand-Arghandab Valley, the application of Landsat imagery and GIS facilitated the assessment of changes in the irrigation system since 1973, which is critical for ongoing agricultural rehabilitation initiatives (Haack et al., 1998). Furthermore, remote sensing and GIS technologies have been employed for counterterrorism efforts in Afghanistan; however, media portrayals have occasionally exaggerated their capabilities (Shroder, 2005). Collectively, these studies illustrate the multi-faceted applications of remote sensing and GIS in southeastern Afghanistan, encompassing environmental monitoring, resource management, and security operations.

Machine learning and statistical regression models

Machine learning and statistical regression models have been implemented to address a range of challenges in Afghanistan, including the prediction of as **climate-related disasters**, estimation of snow water equivalent (SWE). Researchers have employed techniques such as regression analysis on time-series data to predict negative events (Fiok et al., 2020), as well as bagged regression trees and neural networks for the estimation of SWE in watershed areas (Bair et al., 2017). Additionally, random forest classifiers have been utilized to predict LBW in both rural and urban settings (Zahirzada and Lavangnananda, 2021). Machine learning models have further been applied to identify households at risk of food insecurity, achieving an accuracy rate of 80% in the classification of food-insecure households through decision trees and random forest methodologies (Gao et al., 2020). These studies underscore the potential of machine learning and statistical approaches to tackle complex issues in Afghanistan, spanning areas such as environmental monitoring, public health, and food security, by harnessing diverse data sources and predictive methodologies.

Comparative analysis of methodologies

This comparative analysis investigates various methodologies utilized in Southeastern Afghanistan, with a particular emphasis on regional development, infrastructure planning, and education. Regional development policies in Afghanistan and its neighbo-

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ring countries are designed to address socio-economic disparities through initiatives focused on infrastructure development, human capital investment, and regional integration (Kakar and Özçelik, 2024). A decision analysis methodology has been formulated to prioritize infrastructure projects under conditions of volatility, taking into account economic, security, and environmental factors (Javed et al., 2009). In the realm of environmental studies, a comparison of three methods for estimating the slope-length gradient factor across Afghanistan's watersheds indicates that two of these methods are more suitable than the others (Ansari and Tayfur, 2023). Furthermore, an analysis comparing traditional and contemporary mathematics textbooks for grades 7-9 in Afghanistan has revealed enhancements in design and reinforcement of learning; however, challenges persist regarding teaching effectiveness and cognitive appropriateness (Tani, 2013). Collectively, these studies underscore the diverse methodological approaches employed in the analysis of development and education within the region.

Snow load and hazard assessment in Southeastern Afghanistan

Snow hazards represent significant risks in the mountainous regions of Afghanistan. Due to the limitations of ground-based observations, remote sensing techniques have been employed to evaluate both snow load and avalanche hazards (Daly et al., 2012; Caiserman et al., 2022). The Snow Avalanche Frequency Estimation (SAFE) model, which utilizes Landsat satellite data, has successfully mapped avalanche depositional zones over a 32-year period, revealing an average occurrence of 0.88 avalanches per square kilometer annually (Caiserman et al., 2022). Although there has been no significant change in the frequency of avalanches over time, a notable northeastern shift in the locations of hazards has been documented. These snow-related hazards, along with other natural disasters intensified by climate change, threaten lives, livelihoods, and infrastructure in Afghanistan (Ranghieri et al., 2017). The development of risk information and assessment tools are essential for effective disaster management and resilience planning in this vulnerable region. As illustrated in Figure 2, the Hindu Kush region exhibits the highest frequency of snow avalanches, at 0.88 avalanches per square kilometer per year.

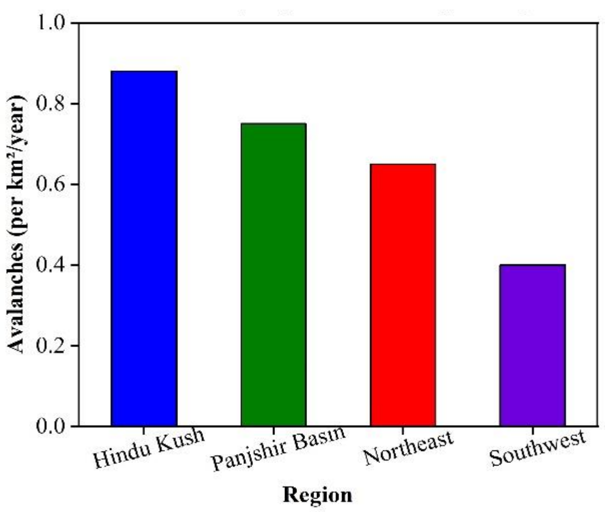

Figure 2. *Snow Avalanche Frequency in different regions of Afghanistan (Caiserman et al., 2022).*

Historical data on snowfall and snow-related hazards

The study of snowfall and associated hazards in southeastern Afghanistan has employed remote sensing techniques to assess snow conditions and evaluate avalanche risks. Since the 2004-2005 season, annual snow assessments have been conducted using multispectral and passive microwave technologies to determine the extent of snow-covered areas and the snow water equivalent in major watersheds (Daly et al., 2012). Furthermore, a 32-year Snow Avalanche Frequency Estimation (SAFE) model, developed through the analysis of Landsat satellite archives, Afghanistan had the highest number of avalanche fatalities since 1990, compared to eight other High Mountain Asia countries. Afghanistan has successfully mapped avalanche frequency and identified vulnerable areas, documenting 810,000 large avalanches since 1990 with a mean frequency of 0.88 avalanches per km² per year (Caiserman et al., 2022). Although there has been no significant change in avalanche frequency over time, a northeastern shift in hazard patterns has been observed. Additionally, an analysis of streamflow characteristics from 79 historical streamgages in northern Afghanistan have provided critical data for effective water management in arid and mountainous environments (Olson and Sether, 2010).

Risk assessment frameworks and mapping

Risk assessment frameworks in Southeastern Afghanistan address a variety of challenges, including illicit crop cultivation and natural hazards. Kienberger et al. (2017) elucidate the intricate interplay of socio-economic and environmental factors that drive opium poppy cultivation, underscoring the necessity for context-specific interventions. Aloko (2018) concentra-

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tes on the construction industry, identifying 21 signify-cant risks that jeopardize project success and advoca-ting for robust risk management practices to mitigate these issues. Ikram et al. (2023) evaluate flood risks and reveal that certain provinces are faced with severe threats due to their high levels of exposure and vulnerability, which necessitates the implementation of targeted flood risk reduction strategies. Finally, Çakıt and Karwowski (2018) utilize a fuzzy GIS approach to delineate risks associated with as climate-related disasters in Afghanistan, identifying high-risk areas predominantly located in the eastern region, which can inform both military and humanitarian decision-making processes. Collectively, these studies emphasize the critical need for integrated risk assessment frameworks that are specifically tailored to address the unique challenges faced by the region.

Challenges and future directions

Estimating ground snow load is essential for conduc-ting snow hazard assessments, yet direct measurements of snow water equivalent (SWE) are frequently unavailable. To address this issue, researchers have developed various methodologies to estimate SWE and snow depth by utilizing diverse data sources and analytical techniques. For instance, Mo et al. (2022) introduced an algorithm that incorporates ground snow depth, precipitation, wind speed, and air temperature to evaluate SWE in northeastern China. Meanwhile, Fridley et al. (1994) detailed a method for correlating water-equivalent depth with snow depth and daily temperature, using first-order station data. In the Hin-du Kush region of Afghanistan, Mahmoodzada et al. (2020) employed Sentinel-1 synthetic aperture radar (SAR) data within a differential interferometric synthe-tic aperture radar (DInSAR)-based framework to esti-mate snow depth during the winter and early melt sea-sons. Furthermore, Tanniru and Ramsankaran (2023) conducted a review of passive microwave remote sen-sing techniques for snow depth, estimation examining various models along with their limitations and challen-ges, particularly in critical regions such as the Himala-yas. Collectively, these studies enhance the methodo-logies for estimating snow load in areas that lack direct SWE measurements. Improved SWE predictions using random forest and neural networks.

Data scarcity and measurement challenges

The estimation of ground snow load plays a vital role in snow hazard assessment and the design of structural systems. However, the unavailability of snow water equivalent (SWE) measurements poses significant challenges. Nonetheless, ground snow depth data can be leveraged to estimate both SWE and ground snow load (Mo et al., 2022; Fridley et al., 1994). A practical algorithm that utilizes variables such as snow depth, precipitation, wind speed, and air temperature has been developed to assess SWE specifically in northeastern China (Mo et al., 2022). In regions characterized by data scarcity, such as Afghanistan, remote sensing tech-niques emerge as valuable alternative solutions. The Snow Avalanche Frequency Estimation (SAFE) model employs Landsat satellite archives to map the frequen-cy of snow hazards and identify vulnerable areas (Cai-serman et al., 2022). Additionally, estimates of passive microwave SWE have demonstrated potential utility in water resource planning within the Upper Helmand Watershed of Afghanistan, where snowmelt constitutes a primary source of water (Vuyovich, 2011). These innovative methods offer promising strategies for estimating ground snow load and evaluating snow hazards in regions where ground-based data is limited.

Need for region-specific modeling approaches

Recent research has underscored the necessity of region-specific methodologies for accurately estimating ground snow loads, taking into account variables such as snow depth and climatic factors. Mo et al. (2022) introduced an algorithm specifically designed for north-eastern China that integrates snow depth, precipitation, wind speed, and air temperature to assess snow water equivalent (SWE). Similarly, Fridley et al. (1994) deve-loped a technique linking water-equivalent depth to both snow depth and daily temperature, utilizing local data sources. Wheeler et al. (2022) established a univer-sal depth-to-load conversion method employing ran-dom forests across the contiguous United States, which demonstrated effectiveness in varying regional con-texts. In Afghanistan, Mahmoodzada et al. (2020) im-plemented a differential interferometric synthetic aper-ture radar (SAR)-based framework utilizing Sentinel-1 data to estimate snow depth within the Hindu Kush Himalayas during peak winter and early melting sea-sons. Collectively, these studies high-light the critical need for customized approaches that account for re-gional climatic characteristics and available data sources to accurately evaluate snow hazards and inform structural design requirements.

Recommendations for improving snow hazard assessment

The assessment of snow hazards in southeastern Af-

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ghanistan is hindered by a scarcity of ground-based observations, thereby necessitating the integration of remote sensing technologies. Since 2004-2005, multispectral and passive microwave data have been utilized to evaluate snow conditions, including snow-covered areas and snow water equivalent, within major Afghanistan watersheds (Daly et al., 2012). The Snow Avalanche Frequency Estimation (SAFE) model, developed using Landsat satellite archives, has effectively mapped avalanche frequency and identified vulnerable areas in Afghanistan over a 32-year span (Caiserman et al., 2022). This model recorded a total of 810,000 significant avalanches, with an average frequency of 0.88 avalanches per square kilometer per year, indicating a northeastward shift in hazard occurrence. Afghanistan holds the unfortunate record of the highest avalanche fatalities (1,057) in the high mountain Asia region (Acharya et al., 2023). To enhance snow hazard assessment, researchers advocate for the development of hazard zonation maps grounded in historical data and modeling efforts, while also emphasizing the incorporation of local and indigenous knowledge in collaboration with community stakeholders.

Conclusions

The precise estimation of snow load and avalanche risks is essential for the effective mitigation of natural hazards in Southeastern Afghanistan. The utilization of remote sensing technologies, including multispectral and microwave data, has considerably enhanced hazard assessments by addressing data deficiencies in this challenging geographical area. The SAFE model, alongside other methodologies, offers valuable insights into avalanche frequency and snow distribution patterns. However, the ongoing impacts of climate change are modifying snowfall patterns, which necessitates the development of adaptive strategies for managing snow-related hazards. Future research should prioritize the integration of machine learning with remote sensing techniques, as well as the refinement of region-specific modeling frameworks. Furthermore, strengthening data collection efforts and fostering collaboration among researchers and policymakers will be crucial for achieving effective disaster preparedness and risk reduction in the mountainous regions of Afghanistan.

Conflicts of interest

The authors declare no conflicts of interest related to this manuscript. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Author Contributions

The contributions of each author to the manuscript are as follows: Nazir Khan Mohammadi was responsible for conceptualization, methodology development, original draft writing, data curation, and visualization. Mohammad Gul Arabzai contributed to the literature review, manuscript editing, validation of findings, and provision of resources. Zikui Wang provided supervision, technical guidance, critical review and editing, and gave final approval of the manuscript. All authors have read and approved the final version of the manuscript.

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