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Journal of Nepal Mountain Academy (NMA) is purely an official publication. As part of NMA's regular academic exercises, it has planned to publish an academic journal annually focusing on mountain science, the adventures and mountaineering. It has aimed at promoting researches in mountain science, socio-culture and tourism activities among the researchers, college and university professors, graduate and undergraduate students, personnel in administrative positions involved in research ventures, and academicians/ professionals immersed in the tourism sectors. As obvious from the title of the journal, mainly research articles from the field of tourism, adventure, mountain science, and mountaineering are preferred for publication.

The articles published in this journal in all its issues are from mountain science, environment, culture and general tourism area. The articles were assigned for peer review to the professors and practitioners in their respective fields, amendments were recommended followed by editorial corrections ensured before they were processed for publication.

However, the editorial team does not bear any responsibility for any incongruences in contents and patterns presented in the articles as they are purely the products of their authors, and hence, the authors are subject to ethical interrogations in the circumstances that are marked to violate ethical parameters applicable in the field of academics and research.

The articles have been arranged in alphabetical order of the authors' name. Researchers and readers are welcome for their any kind of scholarly inquiries and suggestions.

Thank You.

Prof. Dr. Sunil Adhikary

Chief Editor

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Glory of Mera Peak Expedition

This is a high-altitude panoramic image, captured from the summit ridge of Mera Peak (6,476 m) in the Solukhumbu region of Nepal on 07 June 2025. The composition faces northwest and features several iconic Himalayan giants rising above glacial valleys and pro-glacial lakes. Dominating the right-center skyline is Mount Everest (8,848.86 m), whose dark pyramid-shaped summit is slightly recessed. Just south of Everest is Lhotse (8,516 m), distinguishable by its massive bulk and steep south face.

Mountain Coverage

- Nuptse (7,861 m): Runs east to west on the left of Everest.
- Ama Dablam (6,812 m): Famed for its sharp ridges and sacred cultural symbolism.
- Baruntse (7,129 m): East of Ama Dablam, toward the middle-right portion.
- Chamlang (7,319 m): Southeast of Makalu, known as its massive & elegant snow dome.
- Peak 41 (6,648 m): In-between Baruntse and Lhotse.
- Kangtega (6,782 m) & Thamserku (6,608 m): Left mid-ground of the image.
- Pumori (7,161 m): Likely visible on the far-left behind Nuptse.

At the base of the valley below is the Hinku Valley, where the Sabai Tsho and Chamlang Tsho glacial lakes reside. These are pale-turquoise, sediment-laden lakes, fed by melt-water from surrounding glaciers. Their presence reflects rapid glacial retreat and increasing glacial lake outburst flood (GLOF) risk associated with climate change in the eastern Himalayas.



Photo Credit: @Regan Kharel

The panoramic view of the Mahalangur Himal Range from the Mera Peak region, featuring the Mount Everest, Lhotse, and the glacial lakes of the Hinku Valley—an evolving landscape shaped by tectonic uplift and glacial retreat.

Impact of sustainable mountain tourism on economic development: A systematic review

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Abstract

Sustainable mountain tourism focuses on economic, social, cultural, and environmental empowering tools that help to improve the well-being of the mountain community. This study examines the impact of sustainable mountain tourism on economic development using a systematic literature review. The research is based on a review of systematically selected empirical research papers. The Google Scholar search engine was applied using the keywords "tourism policy" and "sustainable mountain tourism". All papers that were published from January 2018 to February 2025 have been checked for the study and 29 research papers were selected for this study using the PRISMA framework. The study find effective governance mechanism and stakeholder engagement are essential factors of sustainable tourism development. The role of governments and stakeholders is crucial in developing and implementing sustainable mountain tourism. Sustainable mountain tourism practices ensure economic stability, empower the local economy and foster livelihood of mountain community. Government and policymakers may introduce economic, social and environmental initiatives to align sustainable mountain tourism practices with the economic interests of the local community.

Keywords: economic development, mountain people, sustainable mountain tourism

Introduction

Sustainable mountain tourism is a priority agenda around the world. It contributes to fostering economic growth while maintaining fragile ecosystems and empowering local communities. Mountain region is rich in terms of natural beauty and cultural heritage that attracts large number of tourists for mountain adventure (Nepal & Chipeniuk, 2005). Mountain people can get benefits from the mountain tourism by leveraging natural and cultural heritage. They may involve in different mountain-based tourism activities and generate jobs, create income, and expand local economies. Sustainable tourism adopts environment friendly practices, promote ecosystems, preserve mountain culture and improve livelihoods of mountain people (Baloch et al., 2023). A global concern for biodiversity and cultural conservation is connected to the growth of sustainable mountain economies through mountain tourism (Ali, 2023; Shokirov et al., 2014).

Mountain region consists of almost 27% of total global land and 54% of the global mountainous part is situated in developing countries. Mountain tourism occupies almost 20% of global tourism and plays a critical role in advancement of global tourism (UNWTO, 2024). Mountainous regions are valuable but vulnerable clusters of biodiversity. Excessive flow of tourists and high economic engagement in mountain tourism is necessary to regulate by governments due to protection of mountain ecosystems and nature conservation. Building

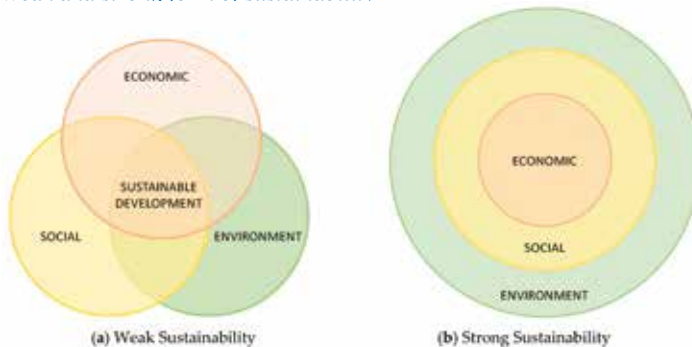
sustainable mountain tourism has induced high concern about protecting heritage and nature through execution of environmental laws (Immerzeel et al., 2020).

Sustainable mountain tourism transforms the people living in rural and mountain region. Mountain people often suffer from low income, unemployment, poverty, limited opportunities, and lack of basic infrastructure. Sustainable tourism enterprises such as homestay, local handicraft, trekking, and other tourism related businesses empower mountain people for their livelihood improvement (Pandiya, 2024). The people living in the mountain region engage in tourism related economic activities and their livelihood status increases. Several studies found a nexus between tourism and economic growth (Brida et al., 2020; Dhungana, 2023; Wu et al., 2022). Development of mountain tourism adheres to sustainability norms, reducing effects on biological resources and ecosystem diversity, supporting the preservation of mountain cultures, and enhancing the welfare of mountain peoples (Boudjemaa, 2023; Nepal, 2002).

Sustainable tourism initiatives help to expand infrastructure in the mountain region. The better road and trekking route, digital transformation, tourist safety, and environmental, social and governance (ESG) practices strengthen mountain tourism. As a result, it promotes the mountain tourism and improves the livelihoods of the people living in the mountain area (Gherdan et al., 2025). It increases growth of tourism based small and medium enterprises (SMEs) that help for the sustained economic growth of mountain regions. The SMEs are related to homestays, eco-lodges, food producers, organic farming, artisans, local tour operators, and other economic activities. Mountain people can be benefited from tourism-based revenue and strengthen local economy. Mountain communities can get economic benefits through community and individual based tourism enterprises that foster to improve local people's livelihoods (Suntikul & Dorji, 2016).

Stakeholders such as local government can promote sustainable mountain tourism activities by empowering local people through sustainable literacy programs in the region. The active engagement of stakeholders such as local community, local level government, local leader, local tourism entrepreneurs, and other stakeholders is crucial for the sustainability of mountain tourism (Purnomo & Purwandari, 2025). The collaboration among the government, tourism entrepreneurs, and local communities is critical to promote sustainable practices and ensure equitable benefits for mountain people (Jamal & Stronza, 2009). Sustainable mountain tourism can be an important tool for inclusive and resilient economic development to empower mountain people.

A sustainability framework of mountain tourism includes economic, social, and environmental magnitude. These approaches focus on the interconnection and balance essential for achieving sustainable development. Economic sustainability includes stable and rational economic growth that foster resource efficacy and innovation to tackle environmental issues in mountain region. Likewise, social sustainability focuses on social unity, empowerment, and cultural preservation to empower local community for their active engagement. Finally, environmental sustainability emphasizes protection of natural resources, ecosystem, and biodiversity and adopts the practices of mitigating environmental degradation and preserving ecosystems through stakeholders' awareness and engagement. Figure 1 shows weak and strong form of sustainability.

Figure 1*Weak and strong form of sustainability**Source: Purnomo and Purwandari (2025).*

There are two models of sustainability: weak and strong. Economic, social and environmental parts are highly separated and few overlapping. It indicates that nature-based capital (environmental factors) can be replaced with human generated capital (economic and social factors). Strong form of sustainability focuses on nestled order in which economy directs within society that survives within the environment. This form of sustainability gives higher priority for environmental protection and social well-being while engaging on economic activities.

Figure 2 reflects the integrated form of sustainability in tourism development that connects economic, social and environmental factors. This model focuses on empowering micro, small and medium enterprises (MSMEs) required for sustained economic growth and resilience. The role of tourism sector is to foster cultural and heritage preservation, empowering local community, enhancing social inclusion, and improving livelihood status of the mountain people. This model integrates economic outcomes as a MSME empowerment, social outcomes as a tourism development, and environmental outcomes as a building sustainable tourism village, highlighted in Figure 2.

Figure 2*Sustainable tourism development framework**Source: Purnomo and Purwandari (2025).*

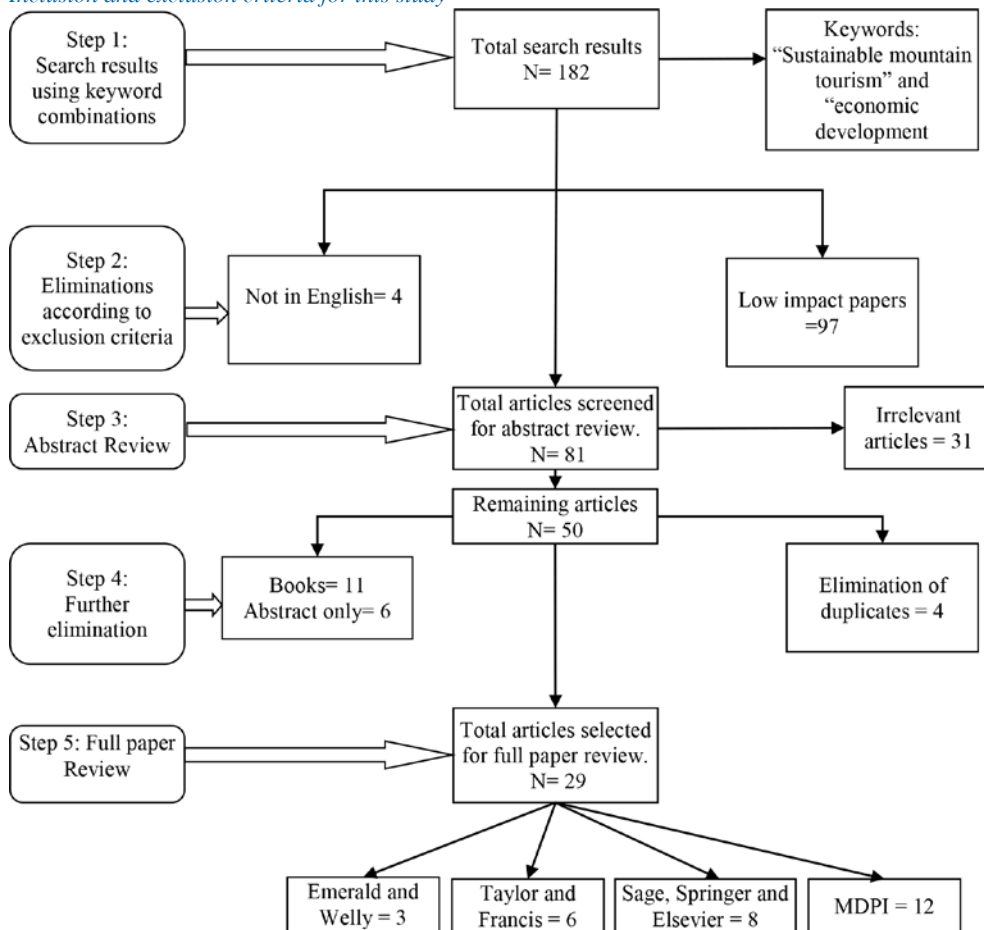
Figure 2 depicts a strong form of sustainability used in developing sustainable tourism with the integration of economic, social and environmental indicators. Economic indicators are related to MSMEs empowerment that encourages local tourism enterprises useful for the livelihood improvement of mountain people. The social indicators, as tourism development factors, are related to community engagement, empowerment, inclusion, cultural and heritage preservation, and benefits to local people. Environmental indicators work as a building effort toward sustainable tourism village that fosters for maintaining ecological health. Sustainable tourism model is viable when it empowers local economies, confirms vibrant social systems, and extends a healthy environment. Integrated policies and stakeholder collaboration is useful to balance economic growth with sustainability in tourism sector.

Sustainable mountain tourism is guided by several theories that support to balance economic, social and environmental integration (Krasnokutska et al., 2024). Triple bottom line (TBL), ecotourism principles, stakeholder theory, environmental justice theory, resilience theory, sustainable livelihood approach, and community-based tourism are the key theories related to the sustainability for mountain tourism (Byrd, 2007; Hall, 2018; Lee & Jamal, 2008; Pforr, 2001; Shen et al., 2008; Stoddard et al., 2012). These theories are critical for promoting mountain tourism and empowering local community through active engagement of stakeholders in sustainable practices.

The primary objective of this study is to investigate the impact of sustainable mountain tourism on economic development. This paper examines the impact of sustainable tourism practices (eco-tourism, stakeholders' engagement, climate resilience, and policy interventions) on economic development (infrastructure development, job creation, revenue generation, and GDP contribution) in mountain regions. The finding of this study shows sustainable tourism influences job creation, income generation, infrastructure development, and national economic strengthening while addressing the issue of sustainable mountain tourism development. This research is expected to contribute valuable insights to the government, policymakers, and tourism practitioners for promoting sustainable mountain tourism and benefiting long-term economic development.

Materials and methods

This study aims to assess the impact of sustainable mountain tourism on economic development. The research is based on a review of empirical studies, reports, and policy documents. The Google Scholar search engine has been used to find research publications on sustainable mountain tourism and economic development. The search keywords are "sustainable mountain tourism" and "economic development" under the domain of the Google Scholar Open Database. All papers that were published from January 2018 to February 2025 have been checked for the study. 182 documents were discovered during the initial inquiry. We removed 97 low-impact articles (beyond Scopus and Web of Sciences) and 4 not in English. Out of 81 documents for abstract review, we further removed 31 irrelevant articles, 11 books, 6 abstracts only, and 4 duplicates. Finally, 29 research papers were selected for this study using a systematic literature review. The inclusion and exclusion criteria for this research are mentioned in Figure 3.

Figure 3*Inclusion and exclusion criteria for this study*

Note:

Adopted a preferred reporting items for systematic reviews and meta-analyses (PRISMA) framework.

Results

Requisites for sustainable tourism and factors attracting mountain tourism

Sustainable tourism is adopting to reduce the environmental influence and to expand the socio-economic benefits. It considers both the promotion and conservation of the tourism industry. Tourism actions are required to be carefully projected, supervised, and observed in a long-term sustainable approach (Kişi, 2019). Sustainable tourism integrates sustainability practices that helps to lowering negative environmental effects and foster the conservation of local and traditional values. For this, stakeholders should encourage innovation and quality standards, emphasis on sustainable accountability, improve skills, encourage sustainable and viable services to the tourists (Roblek et al., 2021). Sustainable mountain tourism requires three key elements- preservation of natural resources, enhancement of living standard of mountain community, and the enrichment of tourist satisfaction (Mutana & Mukwada, 2020).

Mountain tourism is substantially dependent on natural sources and values that are sensitive to climatic changes. It attracts large number of distinct year-round tourists through a wide range of recreational activities such as hiking, mountaineering, biking, rock climbing, and snow sports activities (Steiger et al., 2024). Mountain based characteristics and socio-cultural factors motivate large number of tourists in the mountain region. The landscapes, beautiful and natural scene, fresh air, natural environment, and adventure opportunities attract tourists to observe the mountain closely. Mountain tourism extends a prospect for tourists to pursue wellness especially health-conscious tourist. They may involve themselves in different recreation activities such as trekking, climbing, cycling, adventuring, sightseeing, spa, and relaxing with amazing nature (Zeng et al., 2022).

The requisite for mountain tourism is guided by ecological performance including heritage and cultural landscapes, natural foundation, uniqueness of mountain settings, and active engagement of stakeholders (Dax & Tamme, 2023). Attractiveness toward mountain tourism largely depends on local level factors including monuments, nature, traditions, cultures, local foods, apple and organic farming, quality of foods, reasonable prices that foster tourist high degree of satisfaction (Zeraib et al., 2022). Mountainous rural communities and livelihood improvement is a researchable issue worldwide due to unique mountainous requirements, climatic condition, livelihood improvement, environmental factors, and regional culture (Yang et al., 2024).

Mountain community and sustainable mountain tourism

Mountain community, mostly in developing countries, is facing hurdles due to poor ability to cope with climatic effects. They are highly vulnerable to growing hazards such as landslides, snow falls, rain-on-snow floods, and rock falls. Mountain ecosystems are essential for livelihood improvement, food safety, welfare of mountain community and cultural and heritage protection but confronting rising climate hazards and affected mountain community with a substantial adaptation challenge (Steiger et al., 2024). Basic infrastructure, road facilities and destination accessibility are necessary for tourism industry. However, risks to mountain community from the transport development such as road may result in the loss of business, destroy the ecosystem and affect originality of mountain surroundings (Apollo, 2025).

Mountain tourism suffers from the inadequate transportation system and basic infrastructure. As expansion of transportation and infrastructure in the mountain region, mountain tourism restructured to accessible system of leisure activity that attracts large number of tourists looking for nature-based experiences (Chakraborty & Ghosal, 2024). Women entrepreneurs show a critical role in the extension of sustainable mountain tourism. They have propensity to establish and adopt local stakeholder networks due to high level of authenticity, patience, commitment which are associated to their own ventures (Martini et al., 2020). Young entrepreneurs are engaged in sustainable mountain tourism and align to economic, social, and environment (Ivasciuc & Ispas, 2023). The indicators of sustainable tourism support in shaping tourism intervention strategies with the policy-applicable framework for integrating sustainability into planning and policymaking with the involvement of stakeholders (Jeelani et al., 2023).

Mountain community and livelihood improvement

Cultural, environmental and economic perspective are critical elements for sustainable

mountain tourism that foster local identity, guide behaviours and influence the destination's tourism model (Muchenje et al., 2025). Mountain community often has low income and limited opportunities, mountain tourism provides bundles of opportunity for economic diversification, employment generation and economic transformation of local people (Steiger et al., 2024). With the development of tourism activities in rural areas, it increases employment opportunities and fosters alternative sources to agricultural activities. There is a nexus between tourism development and livelihood improvement of the mountain community (Muresan et al., 2021).

International tourism has a great concern for mountain tourism. The tendencies of tourists have increasingly shifted from sightseeing to mountain outdoor movements such as sports and adventure (Liu et al., 2022). Sustainable tourism development balances economic, social, and ecological expansion to confirm prosper situation for future generations (Wagenseil et al., 2024). The economic aspect of mountain tourism examines the financial sustainability of operations that consists of revenue creation, employment prospects, and local economic growth (Xu et al., 2023). Sustainable tourism ensures to achieve five key indicators: economic, social, cultural, environmental and tourist satisfaction (Milićević et al., 2021).

Sustainable tourism practices and economic development

Economic building is not possible only with the development of the tourism industry, but also strategic initiatives are needed to succeed sustainable tourism ((Kişi, 2019). Mountain route tourism gains economic benefits to the mountain community through sustainable tourism principles (Mutana & Mukwada, 2018). The attitude of the local community and their active engagement towards sustainable tourism support greatly to the expansion of tourism development and long-term sustainability (Muresan et al., 2021). Mountain tourism is significant for the economic growth of mountainous regions (Ali, 2023). The conservation of heritage is crucial for appealing tourists and promoting economic growth. Sustainable tourism policy and its effective implementation balances revenue expansion and cultural preservation (Martins et al., 2025). Sustainable tourism development is significant not only for conserving natural resources and environment, but also for economic empowerment of local community (Bošković et al., 2020; Malec et al., 2024).

Mountain tourism consists of a wide range of natural resources and the sustainability of mountain tourism fosters economic empowerment through tourism-based enterprises. Mountain tourism enterprises can be viable in the long run when they adopt sustainable and integrated strategy (Cristache et al., 2022). Tourism development should support the mountain economy, not damaging natural resources. For this, a sustainable development approach may guide to gain a competitive advantage in the sector (Gajdošíková et al., 2018). Balancing livelihood of mountain community and environmental protection is a crucial task for sustainable mountain tourism. Community driven tourism enterprises can economically empower rural communities (Martins et al., 2025). Tourism entrepreneurship is critical to inspiring household income and promoting gender equality (Ali et al., 2024). Sustainable tourism promotes a sustainable economic model capable of proposing future generations (Simeanu et al., 2025).

Key issues of sustainable mountain tourism

Most developing countries are facing a problem of haphazard development in the mountain region that impacts negatively on local community and the surrounding environment (Mutana

& Mukwada, 2020). Mountain tourism has huge opportunity to promote local economy in terms of job creation, livelihood improvement, and empowering mountain community that may provide substantial benefits. However, raising popularity of mountain tourism can harm nature and ecosystems. Overcrowded tourists in the mountain and only thinking to exploit economic benefits of tourism professionals negatively impact on sustainable mountain tourism (Zeng et al., 2022).

Mountain tourism suffers a wide range of problems such as inadequate infrastructure, poor livelihood status of mountain people, high degree of ageing population, huge number of unemployment, low level of capitalization, and inadequate government support (Cristache et al., 2022). The tourism infrastructure and quality of service strengthens mountain tourism and broadens tourism contributions (Saleem Wani et al., 2023). The interest in economic enhancement through tourism activities can potentially interrupt preservation efforts and conventional livelihoods. The growing tourism industry toward economic development, the necessity for sustainable practices becomes dominant. Expanding roads, managing accommodations, and developing other basic facilities can damage habitats, affect deforestation, and lead to soil erosion. The importance of economic, social and environmental initiatives should be aligned with the mountain tourism activities (Martins et al., 2025).

Strategy for promoting sustainable mountain tourism and livelihood improvement

Sustainable tourism practices are concentrated on product diversification and event management, destination development, promotion and branding strategies, sustainable tourist management system, collaborations, and cooperation with stakeholders (Kişi, 2019). Government organizations and mountain tourism destination executives align sustainable mountain tourism practices with livelihood improvement and local economy empowerment considering natural landscape management and environment protection. Access to transportation is essential in the mountainous region, however transportation policymakers must think about the impact of transportation on the ecological environment (Zeng et al., 2022).

The role of the state (local, provincial, and central) is critical to enhance tourism sustainability and governance in mountain regions. The design of regulations is necessary to align with empowerment of mountain community and ecological protection (Mutana & Mukwada, 2020). To enhance the mountain tourism activities, the role of government and local authority is significant to develop mountain tourism strategies. These strategies include empowering the local community to maintain sustainable practices in the region. For this, active stakeholders' engagement is crucial for raising economic, social and environmental awareness and aligning with the economic interests of the local community. A national strategy is critical to promote mountain tourism through managing and developing basic infrastructure in the region that attracts to engage in tourism activities (Zeraib et al., 2022).

Discussion

Sustainable mountain tourism contributes to fostering economic growth in mountain regions (Zeng et al., 2022). Sustainably managed tourism activities help to increase job opportunities, create employment opportunities and increase income along with conservation of heritage, protection of nature and environment, and promote local culture (Chong & Balasingam, 2019). Sustainable tourism initiatives create economic opportunities and empower the local community. It also fosters tourism-based enterprises including tourism and hospitality,

handicraft and local products, and organic farming (Cole, 2006). Engaging in diverse economic activities empower local people to sustain their livelihood and develop a capacity to adjust for external shocks due to climate change and other vulnerability (Dushkova & Ivlieva, 2024).

Active involvement of the mountain community is crucial for sustained economic growth (Williams & Fennell, 2002). Sustainable mountain tourism behaviour of community ensures economic development in the mountain region (Martins et al., 2025). There is a nexus between sustainability and economic development in the tourism sector (Dhungana, 2023). The role of government and policymakers is crucial in maintaining sustainable practices in the mountain region for sustained economic growth and livelihood at local level (Dhungana, 2024; KC. et al., 2021). Adopting sustainable practices and policies ensures to achieve both environmental and economic outcomes in the mountain region (Brătucu et al., 2017).

Conclusion

Sustainable mountain tourism can work as an economic, social, cultural, and environmental empowering tool that helps to improve the well-being of mountain community. Mountain tourism is progressively striking worldwide due to a wide scale of tourism development strengths due to attraction in snow, natural beauty, diversity of heritage and traditions, rich in mineral and hot springs, and availability of variety of fauna and flora. It attracts a wide range of tourists, and empowers the local economy, however maintaining ecosystems and adopting sustainable practices is a great concern today. Effective governance mechanism and stakeholder engagement are essential factors of sustainable tourism development. The role of governments and stakeholders is crucial in developing and implementing a sustainable framework for sustainable mountain tourism. Building sustainable mountain tourism needs a high degree of commitment and effort from the government and stakeholders. The active engagement of stakeholders for sustainable practices in mountain tourism such as managing sustainable infrastructure, reducing the effect of global warming, adopting long-term viability of tourism businesses, minimizing pollution, empowering mountain community, and collaborating cross-border relationships are crucial. Sustainable mountain tourism practices ensure economic stability, empower the local economy and foster livelihood of mountain community. Government and policymakers may introduce economic, social and environmental initiatives to align sustainable mountain tourism practices with the economic interests of the local community.

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Cryosphere change in the warming Himalaya: Snow cover and snowline trends in Nepal's Langtang Basin (1988-2024)

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Abstract

Snow-Covered Area (SCA) and its migrating lower boundary, the snowline elevation (SLE), are vital indicators of climate change and water availability in mountain regions. We examined the interannual and decadal changes in SCA and SLE in Nepal's Langtang Basin from 1988 to 2024. Using Landsat images and the Normalized Difference Snow Index (NDSI) on Google Earth Engine (GEE), we found that Annual SCA declined from ~200 km² in 1988 to ~128 km² in 2024, with a statistically significant trend of -3.7 km²/year ($p = 0.001$). Snowline elevation rose by approximately +2.24 m/year ($p = 0.088$), indicating an upward shift of seasonal snowpack. These results indicate significant cryospheric changes in Langtang, consistent with regional warming trends. This study highlights the power of open-access satellite data and cloud platforms for monitoring remote mountain environments. Our research supports the International Year of Glacier Preservation (IYGP 2025) and the UN Decade of Action for Cryosphere Sciences (2025-2034).

Keywords: climate change, Google Earth Engine (GEE), Langtang Basin, Snow-Covered Area (SCA), Snow Line Elevation (SLE)

Introduction

Permanent snow and ice sustain glaciers, protect permafrost layers, and regulate water flow (Hock et al., 2019). Rising temperatures have shortened snowfall seasons, altered precipitation patterns, and accelerated snowmelt in mountains (Sun et al., 2024). As a result, warming has contributed to the retreat of snow and glaciers, resulting in decreased snow accumulation and alterations in the phase and distribution of the precipitation (Bolch et al., 2012). In the Himalayas, snow melt contributes up to 40% of streamflow (Chaulagain, 1970; Sasaki et al., 2024; Immerzeel et al., 2009). Understanding changes in snow and ice is critical for communities and ecosystems downstream that rely on meltwater (ICIMOD, 2023).

Satellite remote sensing consistently monitors Himalayan snowfields, which are often inaccessible and have sparse weather stations (Desinayak et al., 2022; Khan et al., 2024). Landsat, with high spatial resolution and reliable cloud masking, provides a strong basis for mapping perennial snow and ice (Khan et al., 2024) and verifying other satellite datasets (Painter et al., 2009; Tuladhar, 2006; Rittger et al., 2021). Comparison between Landsat and MODIS shows that accurate cloud masking is observed in Landsat for a snow-covered area (Stillinger et al., 2019). Therefore, we used Landsat imagery to assess changes in snow cover and elevation in Langtang Basin from 1988 to 2024.

With over 50% of its area covered by snow or ice, Langtang is especially sensitive to cryospheric changes (Pradhananga et al., 2024). According to Brown et al. (2014), glacier melt, snowmelt, and rainfall contribute 62%, 30%, and 8%, respectively, to total surface water in this basin. Our study examines rapid changes in Langtang's snowfields and raises awareness of their impact on livelihoods. This work supports the UN Decade of Action for Cryospheric Sciences (2025-2034) and the International Year of Glacier Preservation 2025.

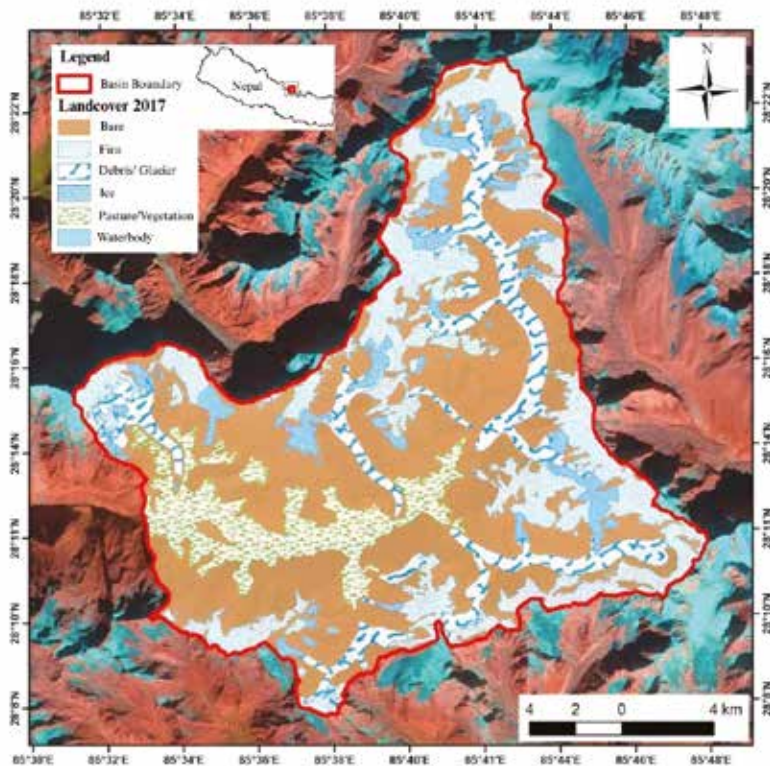
Materials and methods

Study area

The Langtang Basin (Figure 1) in central Nepal ($28^{\circ}08' - 28^{\circ}23' \text{ N}$, $85^{\circ}35' - 85^{\circ}48' \text{ E}$) spans 354 km^2 , with elevations ranging from 3,800 m to 7,234 meters above sea level (m a.s.l.). Approximately 53.5% of the basin is under glacier and snow cover (Pradhananga et al., 2024), and the mean slope is 26.7° (Immerzeel et al., 2012; Pradhananga et al., 2014; Zhou et al., 2014). Figure 2 provides a visual overview of the study area, including the Khimsung Glacier, a meteorological station at Kyanjing, a hydrometric station along Langtang Khola, and glimpses of the challenges local communities face in this high mountain environment.

Figure 1

Location and land-cover map (2017) of Langtang Basin



Note:

The basin boundary is shown by a red polygon.

Figure 2*Khimsung glacier, meteorological and hydrometric station**Note:*

A. Khimsung Glacier, B. Kyanjing Meteorological Station, C. Langtang Khola Hydrometric Station, and D. A glimpse of local livelihoods and climate vulnerability

Climate

Langtang experiences a strong monsoon season from June to September, contributing ~80% of the average 622 mm annual precipitation as observed at the Kyanjing Meteorological Station (Figure 2b) of the Department of Hydrology and Meteorology (Wilson et al., 2016). June to August are the wettest, with persistent precipitation, where daily precipitation amounts generally do not exceed 20 mm/day. In contrast, September and October experience fewer rainy days but higher daily maximum precipitation. During the dry season (November to May), precipitation events are infrequent, primarily snowfall at higher elevations (Immerzeel et al., 2012; Ragettli & Miles, 2015). Precipitation is strongly altitude-dependent, where higher elevation receives more precipitation in comparison to the lower valleys.

Temperature peaks during July and August, and is coldest during December - February (Lamsal et al., 2017). From 1957 to 2002, the average temperature from October to June was 0.5°C, and 8.4°C during monsoon (Immerzeel et al., 2012). Warming and monsoonal precipitation increasingly fall as rain rather than snow, reducing accumulation and raising the snowline.

Methodology

Snow cover was mapped using satellite images in the visible band and the short-wave infrared

(SWIR) bands. This approach leverages the unique characteristics of snow, which has high reflectance in the visible band and strong absorption in the SWIR band. We applied the Normalized Difference Snow Index (NDSI) to identify the snow-covered area (Wang et al., 2022) as:

$$NDSI = \frac{R_{VIS} - R_{SWIR}}{R_{VIS} + R_{SWIR}}$$

Where, VIS = Visible Imagery

SWIR = Short-wave Infrared Imagery

R_{VIS} = Reflectance of the Visible Imagery

R_{SWIR} = Reflectance of the SWIR

We considered a snow threshold value of $NDSI > 0.4$, based on Choubin et al. (2019). We processed Landsat 5 (1987–2011) and Landsat 8 (2013–2024) surface reflectance data in Google Earth Engine (GEE). Images with $<15\%$ cloud cover were selected, clipped to the basin, and combined using median composites. The top-of-atmosphere (TOA) reflectance was computed using official scaling factors, and green and SWIR bands were used for NDSI mapping.

We visualized snow in white and non-snow land surfaces in a red-to-dark-red palette based on SWIR reflectance (Figures 3 & 4). A mosaic was created to highlight the snow-land separation. Trends in SCA and SLE were examined using p-values and Sen's slope; significance was set at $p < 0.05$.

Surface reflectance values were transformed to the TOA reflectance using standard Landsat 5 and Landsat 8 scaling factors to improve cloud and surface assessments. For Landsat 5, NDSI was calculated using band 2 (green) and band 5 (SWIR1); for Landsat 8, bands 3 (green) and 6 (SWIR1) were used.

Data sources

Landsat 5 imagery (1987–2011) and Landsat 8 imagery (2013–2024), with a data gap in 2002 and 2012, were accessed in GEE. With a 16-day revisit cycle, yearly composites were made, and four decadal periods analyzed: 1988–1996, 1997–2005, 2006–2015, and 2016–2024. The data gap (2002 and 2012) remains a limitation, though interpolation across years reduces its overall impact.

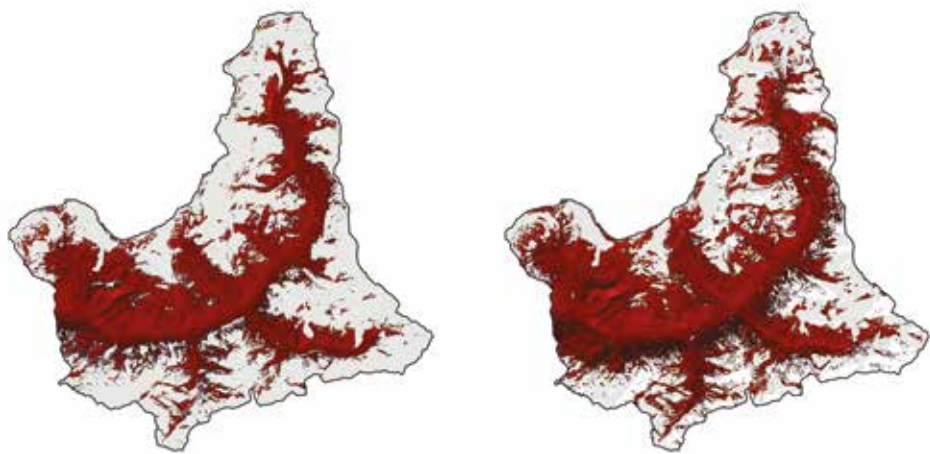
Results

Snow cover map of Langtang Basin

The snow cover maps (Figure 3) generated from Landsat Imagery illustrate notable spatial and temporal changes in snow distribution across the Langtang Basin. In 1988, the basin exhibited widespread snow coverage, particularly in higher elevation zones, with a total snow-covered area (SCA) of 200.4 km². In contrast, the 2024 map shows a significantly reduced snow cover extent of 128.2 km². This substantial decline of approximately 36% over the 36 years underscores the substantial retreat of snow-covered surfaces, likely due to the impacts of regional warming and changing precipitation and snow accumulation dynamics. The retreat is particularly visible at mid and lower elevations, with snow now concentrated primarily at higher altitudes.

Figure 3

Langtang Basin snow cover map



Note:

Snow cover map of 1988 (L) & 2024 (R).

Decadal snow-cover map

As shown in Table 1 and Figure 4, the snow cover area was relatively stable or even slightly increased in the 1990s, with a peak in the 1997–2005 period (240.7 km²). However, after 2005, there is a clear downward trend, with a 28% reduction from 1997–2005 to 2016–2024. The reduction is most evident in mid-altitude regions and valley floors.

Table 1

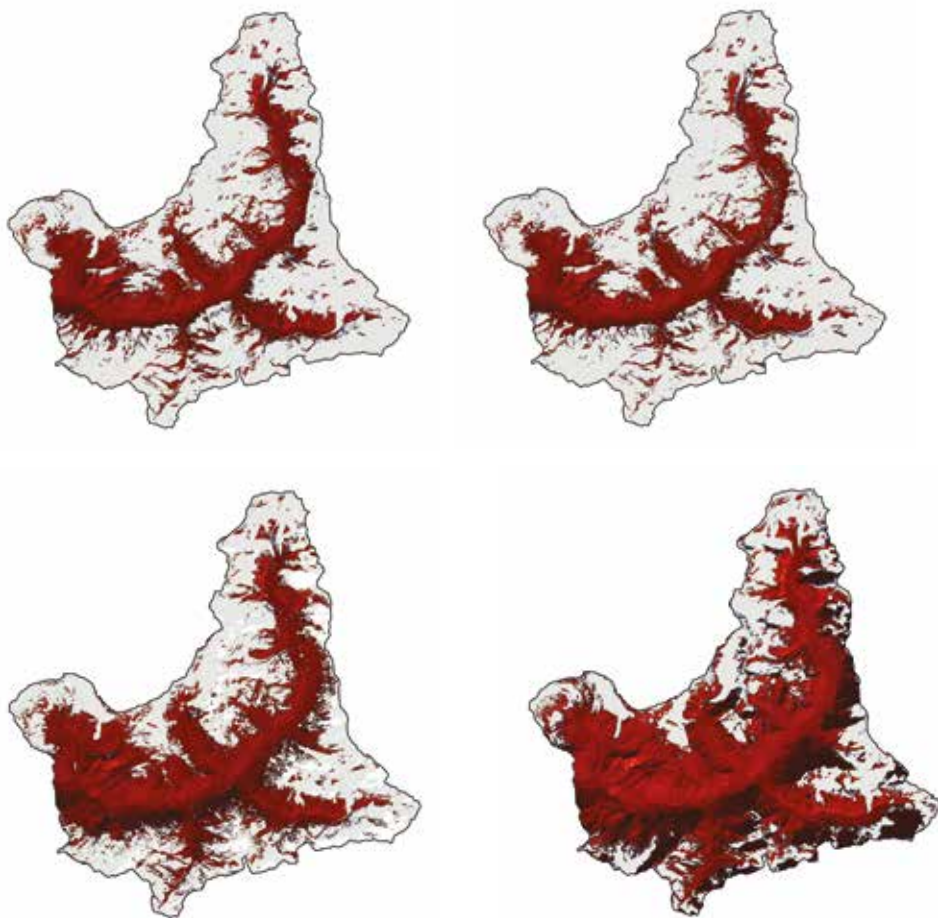
The median decadal snow-covered area of the Langtang Basin

Decade	SCA (km ²)
1988-1996	229.3
1997-2005	240.7
2006-2015	175.8
2016-2024	154.5

This visual and quantitative representation highlights a shrinking snow-covered area and an increasingly exposed terrain, particularly at lower and mid-elevations. The reduction of snowfield area may significantly influence glacier mass balance, streamflow seasonality, and water availability in downstream regions.

Figure 4

Decadal snow cover maps of Langtang Basin



Note:

Decadal snow cover maps using Landsat imagery for (a) 1988 -1996, (b) 1997 - 2005, (c) 2006 - 2015, & (d) 2016 - 2024.

Snow cover area and snowline elevation graphs

Annual variations in SCA and minimum snowline elevation from 1988 to 2024 are presented in Figure 5. The analysis reveals notable interannual variability in snow cover extent, with frequent values below 200 km² after 2010. A statistically significant declining trend in SCA is observed ($p = 0.001$), at a rate of approximately 3.7 km² per year.

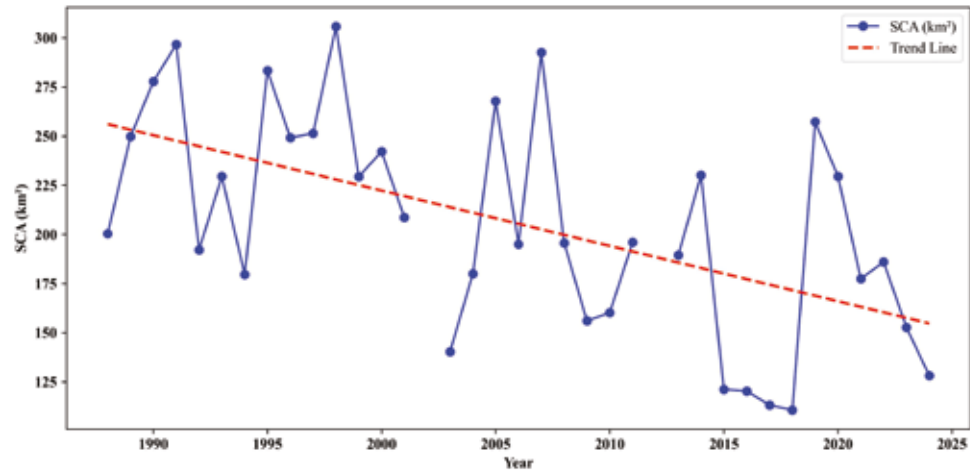
In contrast, the minimum snowline elevation has exhibited an upward trend, from around 4875 m in 1988 to over 5075 m in 2024, with a calculated rate of 2.24 m/year. However, this trend is not statistically significant ($p = 0.088$), likely due to data gaps (e.g., missing imagery in 2012) and cloud interference.

The graphs also reveal an inverse relationship between SCA and snowline elevation: years with lower snowline altitudes generally correspond to higher SCAs, and vice versa.

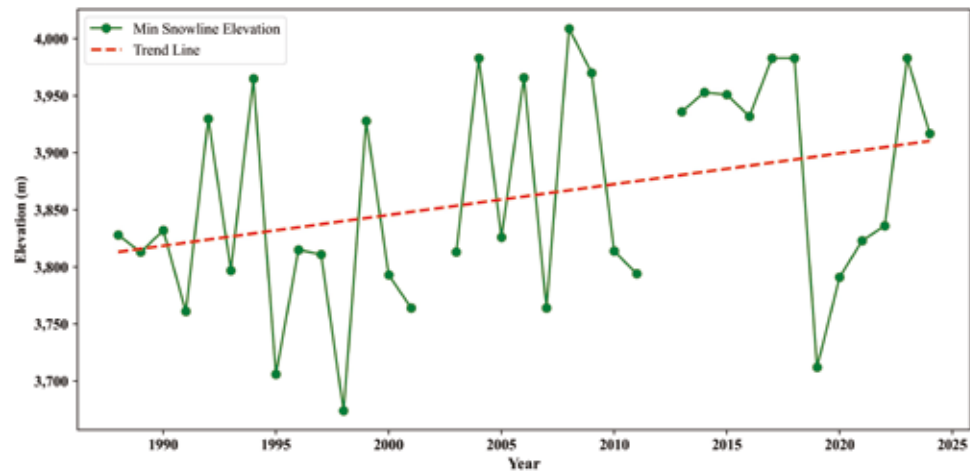
Figure 5

Snow-covered area and snowline elevation

A.



B.



Note:

A. Annual variation in snow-covered area, and B. Minimum snowline elevation (m a.s.l.) in the Langtang Basin (1988–2024).

Snow cover area and snowline anomalies

Figure 6 presents the anomalies of SCA and snowline elevation relative to the long-term means. The mean SCA over the study period was 230.2 km². Between 1990 and 2001, most anomalies were positive, indicating above-average snow cover, except in 1992 and 1994.

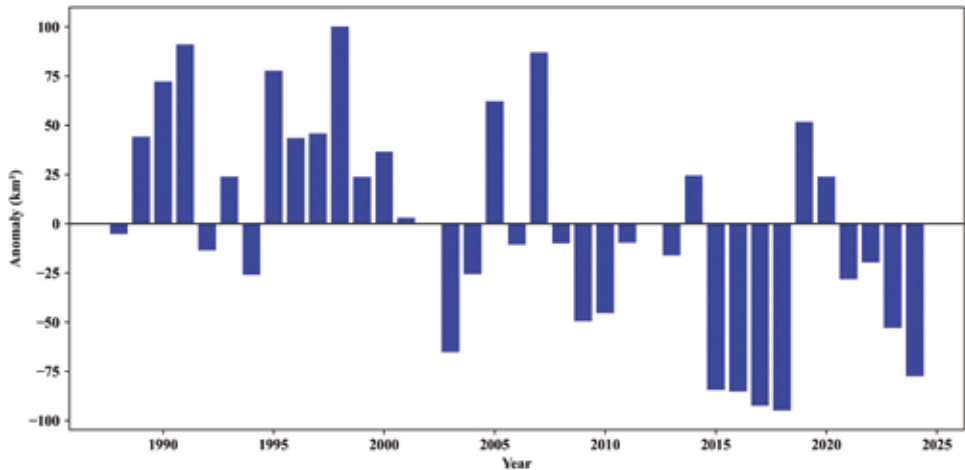
From 2003 onward, however, the anomalies are predominantly negative, indicating widespread snow cover loss.

The snowline elevation anomaly graph (Figure 6b) shows that from 1990 to 2002, the snowline was frequently below the mean, while from 2003 to 2024, positive anomalies dominate, suggesting an upward snowline trend consistent with warming conditions.

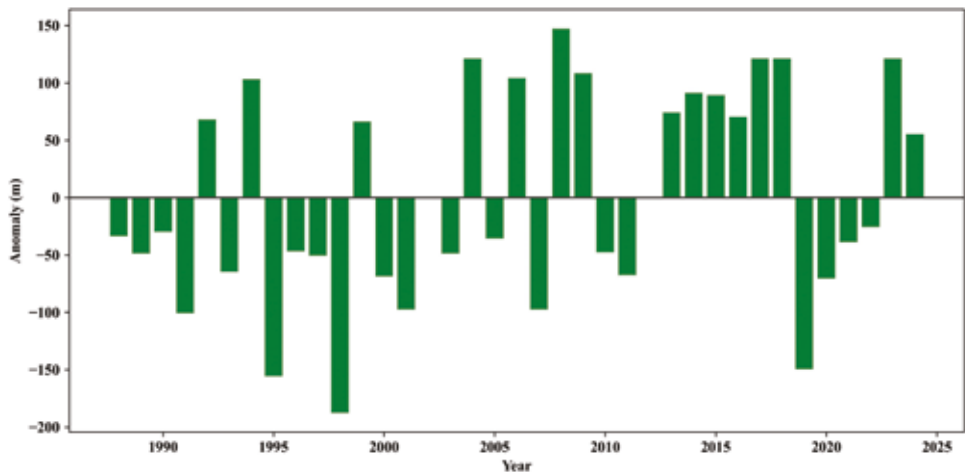
Figure 6

Snow-covered area and snowline elevation anomalies

A.



B.



Note:

A. Snow-covered area anomalies, and B. Snowline elevation anomalies in the Langtang Basin (1988–2024).

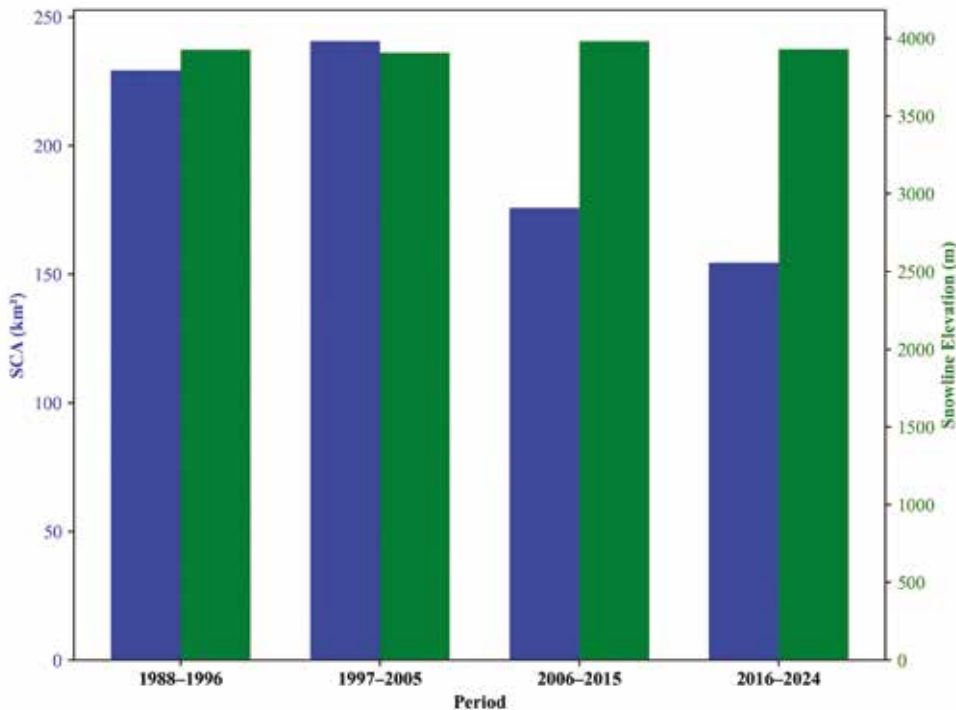
Decadal change

Figure 7 illustrates the decadal average values of snow cover area and snowline elevation. From 1988 to 1996, the basin had an average snow cover of 229.2 km² and a snowline elevation of approximately 4000 m. A slight increase in snow cover was noted in the 1997–2005 period (240.7 km²), with snowline elevation remaining relatively stable.

However, substantial reductions in SCA occurred in the last two decades (2006–2015 and 2016–2024), with averages below 200 km², while snowline elevation showed a gradual upward shift.

Figure 7

Decadal (1988–2024) trends in snow cover and snowline



Note:

A. Decadal (1988–2024) trends in snow cover area (blue), and B. Mean minimum snowline elevation in m a.s.l. (green).

These trends suggest a significant impact of climate warming, potentially enhanced by anthropogenic factors such as the combustion of biomass fuels. The loss of snow cover not only alters hydrological regimes but also poses risks to ecological systems and water-dependent communities.

Discussion

The analysis confirms a statistically significant declining trend in snow-covered area in the Langtang Basin from 1988 to 2024, with an average reduction of 3.7 km² per year. The

snowline elevation shows an upward trend of 2.24 m per year, although it is not statistically significant ($p = 0.088$), likely due to data limitations and image gaps and cloud masking constraints.

These findings align with several past studies:

- Shrestha & Joshi (2009): Found decreasing trends in snow cover and increasing snowline elevations in the Langtang and Khumbu regions using Landsat and MODIS data. However, they warned of MODIS overestimations (~15%) and sensitivity to short image time series.
- Devkota & Shakya (2023): Reported peak snow coverage between February–April and declining snow duration (~40%) between 2000–2017, with greater reductions during the dry seasons.
- Gurung et al. (2017): Using MODIS, reported decreasing snow cover across the Hindu Kush Himalaya, including a decadal average of 4476.5 km² in the Gandaki basin from 2003–2012.
- Thapa et al. (2020): Validated a significant reduction in snow cover during winter and monsoon using the Mann-Kendall and Innovative Trend Analysis methods—findings echoed in this study.
- Khadka et al. (2020): Documented a post-monsoon snowline elevation trend of +33 m/year in western/central and +67 m/year in eastern Nepal (2003–2018). Their MODIS-based study also noted issues with cloud masking, which is relevant here as well.

Despite using high-quality Landsat imagery and GEE, limitations include in medium-resolution imagery:

- Gaps in temporal coverage (e.g., no Landsat data in 2012),
- Cloud masking issues (limited to <15% cloud cover, no image in 2002),
- Challenges in snowline detection in steep, complex terrain.

In mountainous basins like Langtang, logistical constraints and harsh climatic conditions further complicate ground validation. Moreover, the relatively constant decadal snowline in the maps may reflect limitations in accurately capturing snowline positions from medium-resolution imagery.

Conclusion

This study assessed long-term variations in snow cover area and snowline elevation in the Langtang Basin from 1988 to 2024, using Landsat satellite imagery and Google Earth Engine. The findings demonstrate a statistically significant decline in snow-covered area, decreasing at a rate of ~ 3.7 km²/year. Snowline elevation rose by approximately ~2.24 m/year, though the trend was not statistically significant ($p = 0.088$). The decline in snow at mid and lower elevations signals major hydrological and ecological shifts, with implications for water resources and disaster risk. The visual and quantitative results illustrate the increasing vulnerability of the cryosphere in the Himalaya and the importance of continued monitoring.

Despite limitations such as cloud interference and missing years, GEE and Landsat provide

powerful tools for cryosphere monitoring. Future research should integrate higher-resolution, multi-sensor datasets (e.g., Landsat + MODIS + Sentinel) with in-situ validation to improve the robustness of snow trend analysis in mountain basins.

Acknowledgments

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Red panda conservation and climate change in Dhorpatan Hunting Reserve: Integrating community knowledge and land use change

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Abstract

This study explores the perceptions of local people on climate change and red panda conservation in Dhorpatan Hunting Reserve (DHR), Nepal, emphasizing the integration of conservation knowledge and land-use changes. Using GIS-based land-use change analysis, climate data assessment, and socio-ecological survey, the study evaluates habitat alterations from 2017 to 2023 and their implications for red panda population. Similarly, peoples' perceptions on red panda conservation were assessed through interviews and focus group discussion in six villages within DHR. Habitat loss, decline in Nigalo (Himalayan bamboo) coverage, and increase in Nigalo flowering incidences were identified as major threats to red panda in the region. Anthropogenic disturbances, including livestock grazing, resource extraction and other human activities, further exacerbate these challenges. Findings indicate significant land-cover changes, such as reduced rangeland and snow-ice areas and increased tree cover and bare ground. Climate analysis reveals fluctuating rainfall trends across meteorological stations, with localized impacts on vegetation and habitat suitability. Results show limited awareness of conservation practices but a strong cultural connection with the species depicting the need of the community-based conservation approaches. The study underscores the importance of integrating local knowledge into conservation strategies to address threats like habitat fragmentation, climate change, and anthropogenic stressors.

Keywords: climate change, community perception, community-based conservation, habitat, red panda

Introduction

Protected areas and their buffer zones play a critical role in species conservation in the Himalayan region (Bhusal, 2014). However, only 18% of species' habitats fall within protected areas, leaving a significant portion outside these zones (DNPWC, 2022). Human activities, including resource extraction by indigenous communities residing within protected areas, further exacerbate the vulnerability of these ecosystems. Furthermore, anthropogenic stressors within protected areas further exacerbate the vulnerability of these ecosystems. The anthropogenic activities, combined with global environmental changes such as climate change, pose significant threats to biodiversity (Dawson et al., 2021; Pereira et al., 2024; Tiwari et al., 2020). Moreover, allowing certain human activities within protected areas, coupled with low conservation awareness among some of the local communities residing near outskirts create additional challenges for conservation efforts. This highlights the need for an integrated approach that balances biodiversity conservation with human livelihoods while also enhancing awareness and engagement among local communities.

Red panda (*Ailurus fulgens*), the most elusive and unique species, is recognized for its distinct appearance and ecological significance (Yonzon, 1989). Distributed across five countries in the Himalayan region, this species is facing significant threats due to the global environmental changes, habitat competition with domesticated animals, conflicts with other wildlife, and poaching pressures. Despite their wide geographic range over the Himalayas, they are distributed unevenly and found at low density (Shrestha et al., 2020). However, because of its habitat loss and fragmentation, red panda falls under endangered category of IUCN, red list. Threats like illegal trade and demand for pet animals are now more serious threats in Nepal than in other distribution countries (Badola et al., 2020).

Global climate change further endangers red panda and their habitats (Basumatary et al., 2021). In parallel, some of the listed endangered faunal species are at a high level of threaten due to the change in climatic conditions that have impacted the vegetation of their habitats (Bista et al., 2017, Pradhan et al., 2001). Although the red panda being listed as one of the 27 protected species, its population is steadily declining due to multiple threats. These include forest fires, rotational grazing, slash-and-burn cultivation, timber and firewood collection, predation by dogs, natural die-off of Nigalo (Himalayan bamboo) species, inbreeding depression, drought, landslides, agricultural expansion, lack of awareness, and development activities (Bista et al., 2017; DNPWC & DFSC, 2018; Wei et al., 1999). In the key conservation areas such as the Kanchenjunga Conservation Area, Dhorpatan Hunting Reserve, Sagarmatha region, and Central Himalayas, major threats include livestock grazing, habitat destruction, and fragmentation, heavy reliance on forests for firewood and construction materials, and harmful local practices, such as chasing and killing panda (Acharya et al., 2018; Mahato et al., 2011; Subedi & Thapa, 2011).

Red panda presence has been recorded in 24 districts and 7 protected areas with potential habitat of approximately 23,977 km² (DNPWC & DFSC, 2018; Panthi et al., 2019; Thapa et al., 2018) across Nepal's mid-hill regions. Some studies also indicate the presence of red panda outside protected areas and their buffer zones (Thapa et al., 2018). Despite its wide distribution, most conservation efforts are predominantly concentrated in eastern Nepal, particularly in Pachthar-Ilam-Taplejung (PIT) Corridor. Additionally, limited conservation initiatives have been carried out in the Gaurishankar Conservation Area (GCA) and Langtang National Park (LNP). In contrast, in western Nepal, where studies have identified potential red panda habitats and occurrences, there is a notable lack of conservation programs, particularly community-based initiatives. Most of the studies on red panda are focused mainly on proxy sources like fecal droppings and pugmarks (Pradhan et al., 2001; Shrestha et al., 2021; Yonzon & Hunter, 1991) as well as interviews with local stakeholders. This study aims to address this gap by exploring local conservation knowledge, understanding how communities perceive this elusive species, and assessing their awareness of habitat changes in areas with potential red panda presence. Focusing on these dimensions, the research aims to contribute to the development of targeted conservation strategies that engage local communities and promote the long-term survival of red panda in the western Nepal. This study has identified local conservation knowledge on red panda and its importance on cultural and sustaining ecosystem to ensure the species long term survival.

Materials and methods

Study area

Dhorpatan Hunting Reserve (DHR) is located at 82°50' to 83°15' East longitude and 28°30' to 28°50' North latitude, along the Central Himalaya (Figure 1). The elevation of the reserve ranges from 2000 m (Taksera) to 7246 m (Putha Himal) above sea level encompassing diverse topography including valley, rangeland ridges and steep slopes (Aryal et al. 2010; DHR, 2019; Kandel, 2000). DHR is the only hunting reserve in Nepal that permit sport hunting of Blue sheep (*Pseudois nayaur*) and Himalayan thar (*Hemitragus jemlahicus*) with an area of 1325 km² and 539.04 km² area as proposed buffer zone. This reserve encompasses diverse topography and microclimates, supporting various endangered and protected faunal species. However, human access to the reserve for grazing and resource extraction presents ongoing conservation challenges (Rai, 2024). The reserve is significant for its biocultural diversity. It harbors large numbers of rare, endangered, endemic medicinal plants and animals. The reserve covers three districts- Baglung, Myagdi and East Rukum of Gandaki and Lumbini Provinces of Nepal. The study focused on community, community practices and conservation on red panda within three different blocks of DHR, which is located in the western region of Nepal.

Besides from red panda, the reserve is home to a variety of protected wildlife species, making it a significant biodiversity hotspot. Large mammalian fauna present in the area include Himalayan tahr (*Hemitragus jemlahicus*), musk deer (*Moschus* sp.), and Himalayan black bear (*Ursus thibetanus*) (Kandel, 2008; Karki & Thapa, 2013). DHR also has access to human for the resource use like grazing and extraction of other resources (DHR, 2019). The livelihood highly depends on high-altitude forests and rangelands, which are also used for the traditional livestock herding and collection of value medicinal plants, firewood and building materials (DHR, 2019; Sharma & Belant, 2010).

Figure 1

Study area map showing major settlements inside the hunting reserve



Data analysis approach

The ecological and climatic factors influencing red panda conservation in the DHR, as well as the perspectives of the local population, were assessed using a combination of socio-ecological surveys, land use change detection, and climate data analysis. Historical rainfall data was obtained from the Department of Hydrology and Meteorology (DHM), Nepal, in order to investigate long-term climatic changes affecting red panda habitats. Rainfall data for the research came from eight local meteorological stations: Bobang, Gurja Khani, Dunai, Muna, Shera Gaun, Rukumkot, Baghara, and Libang Gaun. Thession polygon technique in ArcMap 10.8 were utilized to identified the spatial extent of rainfall station covering full extent of DHR. K-Nearest Neighbors (KNN) imputation method was applied in R using VIM package (Kowarik & Templ, 2016) for imputation of missing rainfall data. Information on precipitation patterns over DHR was obtained by spatial interpolation, which was used to build a rainfall map. A basis for comprehending possible climate-related habitat changes impacting red panda populations was established by this precipitation study. To assess land use and habitat change over time, satellite imagery from Sentinel-2 L2A (2017 & 2023) was downloaded via the ESRI platform (ESRI, 2025). A change detection approach was used to examine changes in land cover, forest degradation, and other landscape alterations potentially affecting red panda habitats in DHR. This GIS-based approach helped quantify recent habitat variations, indicating possible threats from human activities and environmental changes.

A semi-structured questionnaire survey was used to identify the local conservation knowledge on red panda, opinions on climate change, and human-wildlife interactions. The survey was carried out between October 2022 and April 2023 in six DHR villages: Gurjaghat, Masa, Niseldhor, Pakathar, Syalpakhe, and Sera Gaun. Herders, locals, and informants from the Hunting Reserve Office and ranger stations were among the 55 interviews chosen because of their accessibility and experience with red panda habitats. Data on subjects such perceived climate impacts, habitat changes, and red panda conservation awareness were gathered through in-person interviews using semi-structured questionnaires.

Focus group discussions (FGDs) were also held in Sera Gaun with local leaders for obtaining a wider community viewpoint on conservation concerns and cross-validate individual replies. Due to their seasonal migration from lower land to upland and other different circumstance only 55 people were surveyed. DHM rainfall trends were compared to local opinions of climate change's effects on red panda habitats. The land use change analysis was carried out using GIS-based spatial methodologies to quantify and determine habitat changes. Thematic analysis was used to discover critical trends in conservation knowledge, attitudes, and perceived risks to red panda based on questionnaire survey and focus group data. Ethical concerns were followed throughout the investigation. All participants provided prior informed consent, ensuring that their participation was voluntary. The study adhered to ethical principles for dealing with indigenous groups, respecting local knowledge and cultural sensitivity. The study's findings are likely to help community-based conservation efforts and inform future policy choices for red panda conservation within and outskirt of DHR.

Results and discussion

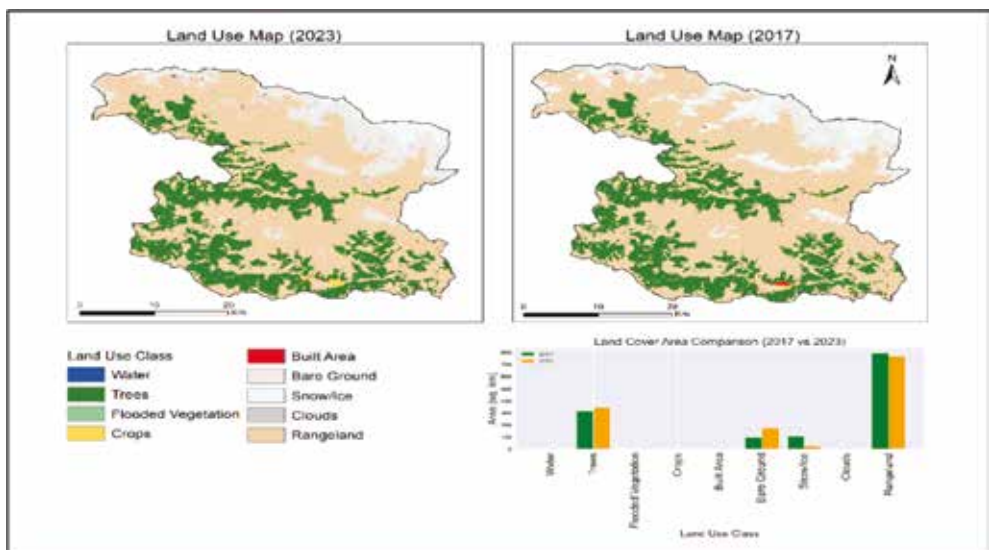
Land use change

Analysis of land use change and quantification of change in land use class are critical for understanding ecological dynamics, and anthropogenic processes in an landscape (Chettri et

al., 2013). Land use change analysis between 2017 and 2023 (Figure 2) of DHR shows a decrease in rangeland (797 to 770 km²) and snow/ice (107 to 27 km²), while bare ground (95 to 176 km²) and tree (345-319 km²) areas have expanded, particularly in the southern region with minor change in other land use class. The bar chart illustrates such changes, revealing an increase in tree cover and bare ground and decrease in rangeland and snow/ice cover. Similar type of result recorded by Sharma et al. 2019 in DHR with nearly 2% increase in forest area but contradict with the result of declining snow/ice cover as they calculated 0.42% increase in snow/ice cover. Similarly, correlating the major habitat of red panda, forest cover, which changes or altered in a span of five years could significantly impact the habitat as it could possibly shift the niche and could create conflict between them or within other animals. Furthermore, in protected area for instance DHR, such change in land use and cover cause significant impact and make vulnerable to the species. Land cover change has been one of the major drivers of change leading to an alteration of critical habitats for many of the threatened species worldwide. Species with a narrow range and specialized habitats are at higher risk (Chettri et al., 2013). Similarly, heat map (Figure 3) describes the significant changes occurred in rangeland and snow/ice areas, with 37.56 km² of rangeland and 43.96 km² of snow/ice transitioning to bare land. Following bare ground conversion, Snow/ice notably converting to rangeland (31.91 km²). Trees experienced some conversion (10.05 km² shifted to rangeland and 34.45 km² rangeland converted into tree.

Figure 2

Land use changes between 2017 and 2023 in DHR



Note:

Sources - Sentinel Image-2 L2A (2017 & 2023).

Figure 3

Heatmap showing land use change in Dhorpatan from 2023 to 2017 in km2



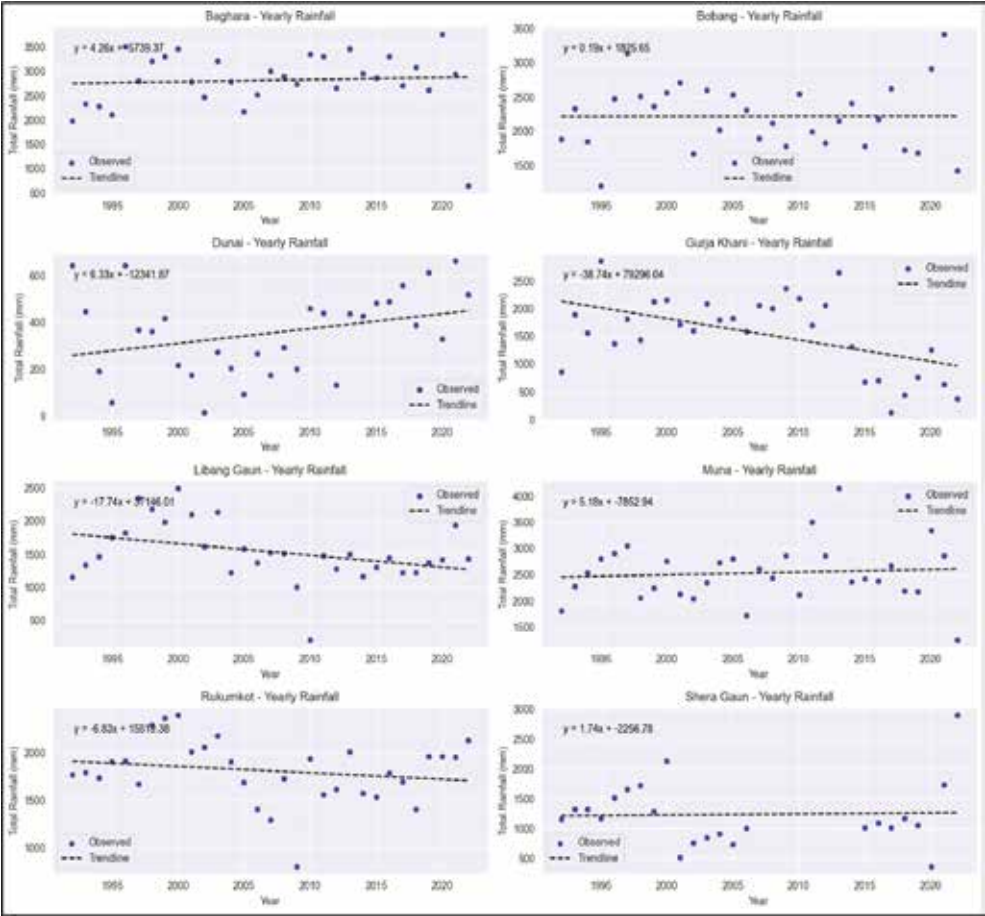
Changes in climatic variables

The climatic variable are major predictors that largely determine habitat suitability at a landscape level and are major components in the determination of vegetation composition and habitat (Thapa et al., 2018). The rainfall trends in Bhagara, Sheragaun, Dunai, and Muna showed an increasing pattern, reflected by their positive slopes. Bobang, however, showed only a negligible increase. In contrast, Gurja Khani, Libang Gaun, and Rukumkot exhibit decreasing trends, with Gurja Khani experiencing the sharpest decline (slope: -38.74). Among the increasing stations, Muna shows the strongest rise (slope: 5.18), while the remaining stations exhibit minimal fluctuations (Figure 4). Such fluctuation in the trend of rainfall might be due to rough elevation gradient and the location of the station towards windwards and leeward side. In the study by Karki et al. (2017) decreasing precipitation trends in mid-western and trans-Himalayan regions of Nepal was found, while this study shows fluctuating in each station with mixed type trends. A study by Talchabhadel et al. (2018) reported declining precipitation trends in Nepal's mid-western and trans-Himalayan regions, whereas this study reveals mixed trends across stations. The observed fluctuations of increasing spatial variability in rainfall, influenced by elevation differences and shifting monsoon patterns a finding supported by Bista et al. (2023).

Figure 5 shows an interpolated rainfall map of Nepal, indicating the highest average rainfall in the southeastern region of DHR. This pattern likely results from the monsoon's entry point, lower elevation, and the presence of valley areas such as Dhorpatan, along with high vegetation density and minimal barriers to moist air flow. In contrast, the northwestern region experiences lower rainfall, possibly due to its high elevation, mountainous terrain, and leeward positioning. Additionally, snowfall at higher altitudes-particularly in northern areas like Putha Mountain - may further contribute to reduced rainfall measurements.

Figure 4

Annual rainfall trend of nearest 8 stations of DHR

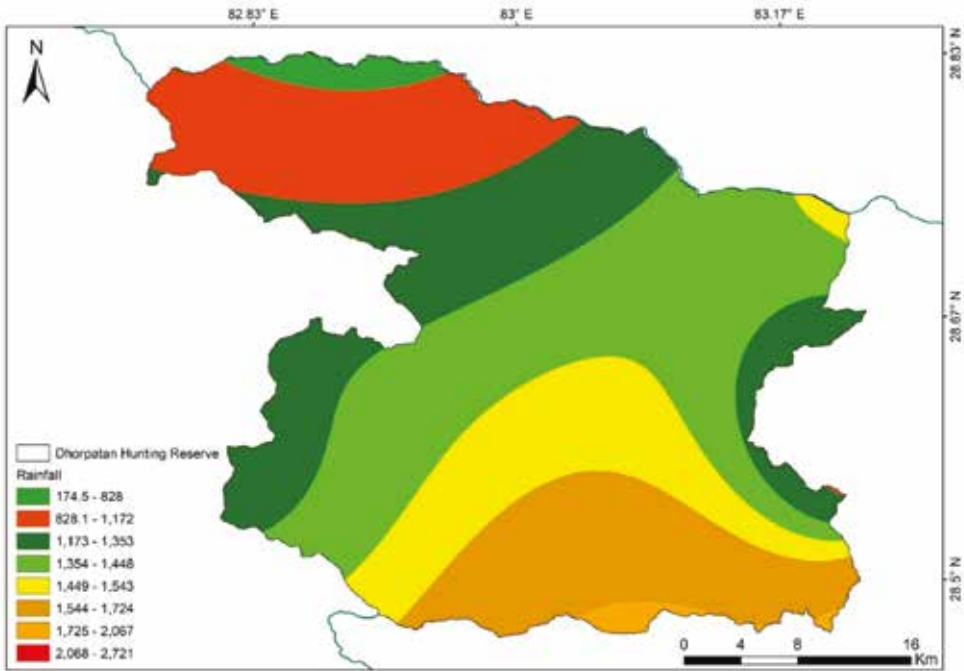


Note:

This figure shows the average annual rainfall trend from the eight nearest rainfall stations around DHR.

Figure 5

Interpolating rainfall over DHR



Note:

Interpolation map of DHR using the average annual rainfall data from the eight nearest stations.

People's conservation knowledge towards red panda and climate change

The level of awareness and conservation knowledge and its ecological significance was found to be low among the villagers. Summer huts made by herdsmen to keep their livestock were scattered in every block which showed that animal husbandry was the main livelihood option for the local people in and around DHR, such process causing a severe threat to wild animal habitats by consumption and destruction of its food. Red panda is a very shy animal due to which livestock might be creating disturbance in their mating activities. During field survey extensive evidence of livestock effects on vegetation included overgrazing and trampling of Nigalo stands was also observed. Due to their seasonal migration from lower land to upland and other different circumstance only 55 people were surveyed. 76% of respondent have heard about red panda but only 52.72% know about distribution and its habitat. Among them, most of the respondents frequently visited the forest (~24%) (Figure 6). 56% of respondents have not seen red panda (Figure 6) Among the people who have observed red panda, most of them observed red panda between 2 to 3 years ago (16%), followed by less than 1 year ago (14%) at DHR (Figure 7).

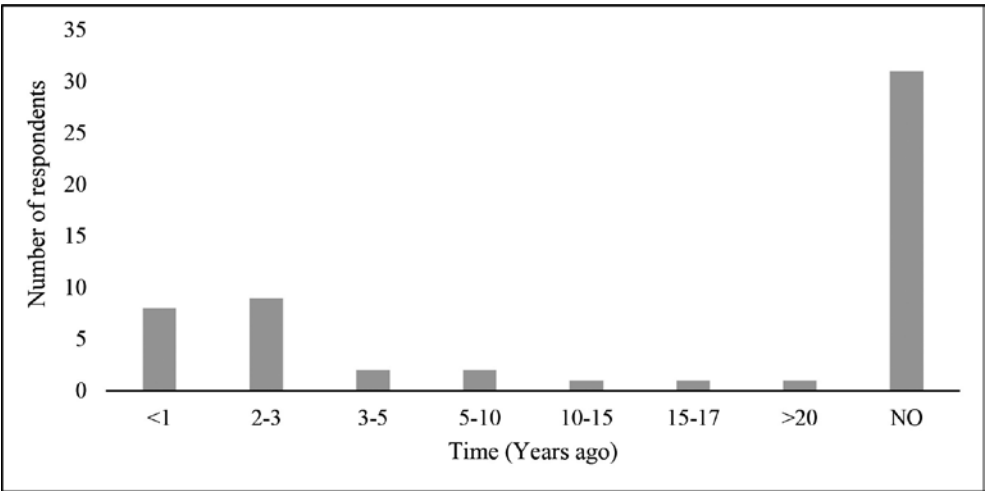
Figure 6

Visit rate of respondents to the forests



Figure 7

Respondents who have seen red panda in and around forests



Similarly, most of the respondent do not know about the status of the number, whether it is increasing or decreasing (56%), while 30% respondent responds reported they are increasing, and 3% respondent communicated that red panda numbers are stable (Figure 8). Additionally, 43% of respondent thought red panda is important for conservation. All the respondent responds as it is important who knows red panda. Different threats identified from survey are: hunting for meat, hunting for cultural values, conflict with domesticated dog, grazing domesticated animal, other wildlife and changing climate. 41% of respondent responded their habitat is decreasing while 29% respondents responded that they do not know about the status of its habitat. Most of the respondents' responded an increase in temperature (58%) and rainfall (40%) pattern while decrease in snowfall (47%) (Figure 9).

Figure 8

People perception about the number of red panda

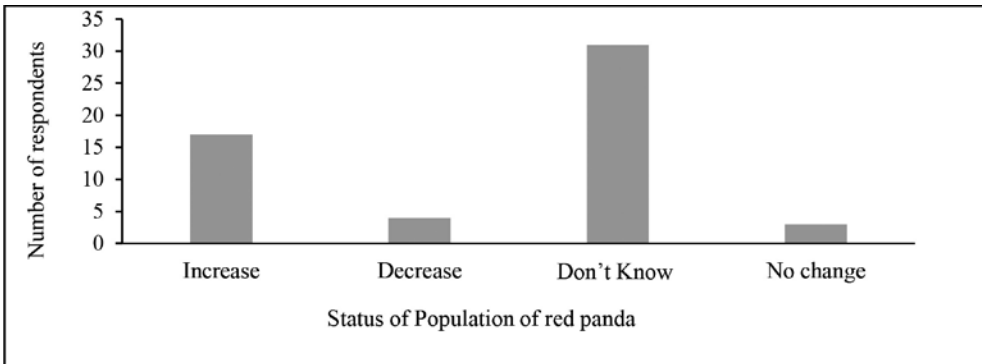
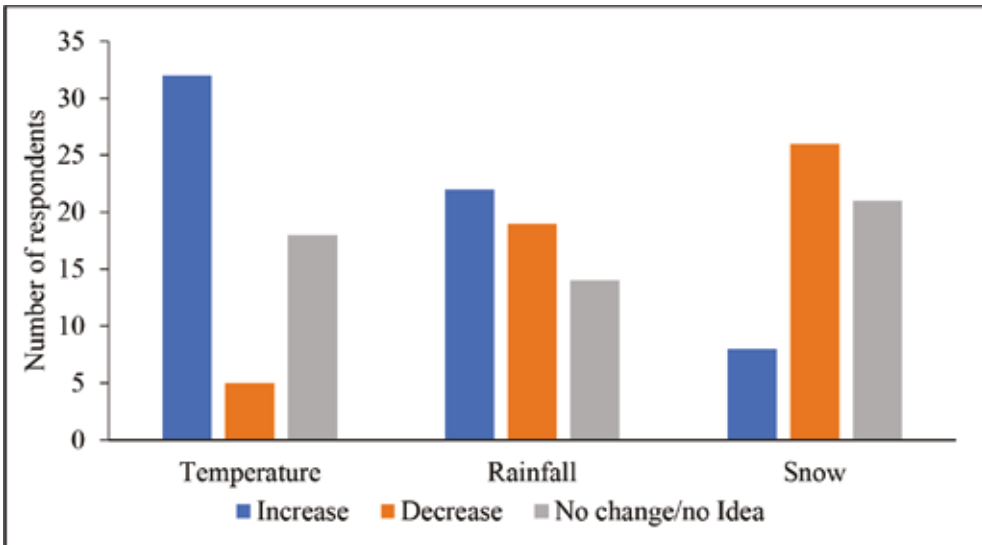


Figure 9

People perception on change in temperature, rainfall and snowfall



Results from the survey on climate and the habitat of red panda, along with the data on rainfall from DHM, reveals clear insight and understanding about the climate change on DHR. Changes in rainfall pattern suggest that, the changes in climatic pattern have likely to change in the structure of vegetation and distribution in the area (Joshi et al., 2019) and potential impact on red panda's habitat and overall ecosystem. As a response to the observed changes in rainfall pattern, red panda might potentially adapt by relocating to higher elevations where vegetation structure is changed. This movement could impact on their food availability as search and depends on new resources to adapt with the changing environment. Further the migration can also be correlate with the change in the forest area. Most of the respondent in this study feel annual rainfall is increasing whereas the number of snowing days, and annual snowfall are decreasing in red panda habitat. Climate is a key ecological factor determining species range distribution thus, the anticipated suitable habitat shift

(latitude and/or elevation) in response to climate change. Climate-related variables offers basic information about suitable habitat for the species and are key ecological factors determinant of species occurrence (Feng et al., 2022). Climatic variable has a significant influence over the growth rates of bamboo coverage (Reid et al., 1991), a dietary staple for red panda (Zhang et al., 2009; Pradhan et al., 2001). Hence, the changes in precipitation might affect adversely like changes in plant competition and growth patterns, plant-animal interactions, and productivity.

Furthermore, transhuman movement during red panda breeding season i.e., May and August poses threats to red panda (Jnawali et al., 2011) as red panda are highly sensitive during breeding. During survey, extensive evidence of livestock effects on vegetation included overgrazing and trampling of Nigalo stands was observed. Also, livestock shelter near the red panda prime habitat also indicates the threats due to livestock grazing pressure, human movement. As observed pelts of red panda in shamans back shows the culturally importance of red panda with its threats of extension. which is also mentioned by Glatston & Gebauer, (2022) as the Northern Magar tribe in Western Nepal, specifically their Ramma or Shamans, incorporate the skin and fur of red panda into their ceremonial attire. During risky rituals performed for healing purposes, the shamans carry the red panda's body on their backs. Similar people beliefs are held by the neighboring Bhuji Khola of Baglung District. During the survey with shamans, it is estimated that there are about 80 shamans in surrounding area of DHR including Baglung and Rukum East Districts. Most of them have the pelts of red panda. Which also poses threats to red panda. Habitat degradation, declining Nigalo coverage, increase incidences of Nigalo flowering, along with illegal hunting by the shepherds and killing by domesticated dog was found as major threats to red panda in DHR.

Furthermore, there is feeble community-based conservation programs and local conservation knowledge assessments in DHR, despite its huge potential as a red panda habitat. This gap requires for comprehensive studies in under-explored regions like DHR, focusing on how local people thought about the red panda and its occurrence and impact of anthropogenic disturbance and other climate related impact is limited. This study suggests to implement community-based conservation programs and promote alternative livelihood options to conserve red panda. Furthermore, it is advised to monitor the population dynamics, distribution, home range, movement pattern and their causal factors, and various multiscale problems associated with conservation of red panda in different areas.

Conclusion

The study identified several threats to red panda in the study area, including habitat loss, decrease in Nigalo (Himalaya bamboo) coverage, and increase in the incidences of Nigalo flowering. Additionally, anthropogenic disturbances such as livestock grazing and direct human disturbances in the habitat were identified as serious threats to their existence. Furthermore, the study revealed an overall decreasing trend in average annual rainfall, which could also potentially impact red panda habitat. The study provides insights pertaining to the distribution, preferred habitat characteristics, and threats faced by red panda in DHR.

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Transforming Knuckles Mountain Range into a sustainable tourism model: A comprehensive framework for ecotourism development

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Abstract

The Knuckles Mountain Range in Sri Lanka is a UNESCO World Heritage site. It has a remarkable combination of biological and cultural features. This paper deals with the problems and possibilities of sustainable tourism in the area by considering community-based Ecotourism development to improve the region's infrastructure. The research revealed the main barriers to sustainable tourism in this region which stem from the lack of infrastructure, environmental abuse, and poor cooperation between stakeholders. By using sustainable tourism approaches such as the Triple Bottom Line (TBL), the DPSIR (Drivers, Pressures, States, Impacts, Responses) model, and the Sustainable Livelihoods Framework, this paper presents a model which would sustain the livelihood of the people of the Knuckles Mountain Range area by converting the area into a tourism destination. This model prescribes the development of infrastructure, eco-tourism, local community participation, and policy. This research case elucidated on the importance of resolving the paradox between maintenance of ecological soundness and impactful socio economic activity where the advantages of tourism are maximized but the tourism impact on the unique nature and sociocultural heritage is minimized. The results form a part of ongoing discussions in sustainable mountain tourism development in other parts of the world, providing guidance for regions struggling with the dual issue of tourism development and environmental sustainability.

Keywords: community engagement, eco-tourism, environmental conservation, mountain, sustainable tourism

Introduction

The Knuckles Mountain Range, which is in the heart of the highlands of Sri Lanka, is a UNESCO World Heritage site and an Outstanding Area of Natural Beauty (Ruzaik, 2023). Possibly as a result of its rich biological and cultural diversity conservation, the range is considered a biodiversity hotspot (Dassanayake, 2023). With an approximate area of 21,000 hectares, the range is known for its beautiful views and is often referred to as the 'Dumbara Kanduvetiya' because the peaks of these ranges are usually covered with a foggy mist. This range receives its name because when viewed from certain angles, it looks like a person's knuckles. This region is a major hotspot for many endemic and endangered species with over 1000 plant species such as endemic rare orchids, and wildlife like the Sri Lankan leopard, elephants, and other bird species (Gunatilleke et al., 2017). The Knuckles Range is also well known for its special temperature and precipitation conditions. The climate varies greatly even over short distances within the range of montane forests and savannahs. The range is significant historically as well. It had been a major site for ancient civilizations and had been

important for the few located there for economic and strategic purposes. The area still retains a large variety of folklore and has rich cultural traditions.

The challenges facing the Knuckles Mountain Range in sustainably practicing mountain tourism stem from a mixture of factors, including a lack of infrastructure, poor servicing of tourists, inadequate stakeholder coordination, and the lacking appreciation and knowledge of sustainable tourism (Siriwardana, 2019; Jayamanna et al., 2023). All of these variables together harm the natural resources in this region, which bears some of the most breathtaking beauty the world has to offer. To begin with, the barriers to visitors' and local communities' understanding and appreciation of the importance of conserving the ecosystems in the Knuckles Mountain Range primarily stem from issues such as cardamom deforestation, illegal logging, and careless waste management practices that have become common due to tourism activities. What remains highly troubling is how these sociocultural and economic factors have greatly been exacerbated during the global pandemic. For instance, in New Zealand, the pandemic led to a shift in tourism trends, with a greater focus on sustainability, which was necessary to support the tourism recovery and environmental resilience (Baum & Robinson, 2024). Similar changes have been observed in the Himalayas, where tourist behaviours adapted post-pandemic, demanding more sustainable practices to protect natural resources. The challenges described above can lead to severe consequences for Sri Lanka's ability to preserve its natural beauty and develop a sustainable conservation economy through tourism.

The necessity of conserving the Knuckles Mountain Ranges to maintain ecological harmony cannot be overstated. It is home to a host of flora with a wide variety of plants, many of which are specific to the area. This includes more than one thousand and forty-one species of plants belonging to one hundred forty-one families, of which one hundred sixty species are classified as endemic (Seifollahi et al., 2023). The Knuckles Mountain Range in Sri Lanka harbors a rich variety of fauna, including around 200 species of birds, 31 mammals, and numerous reptiles and amphibians. However, these species face significant risks due to human activities such as reckless slash-and-burn farming techniques and deforestation for development and urbanization, which threaten their habitats and biodiversity (Dayananda, Perera, & Senevirathne, 2023).

The main goal of this inquiry is to create an all encompassing model for developing the Knuckles Mountain Range as a sustainable mountain tourism destination. This study, however, seeks to analyse the hopes and the gaps that the visitors of the Knuckles Range have with regard to the existing tourism infrastructure, services, sustainability measures and articulate strategies and actionable recommendations for sustainable tourism growth within the region.

The research will seek to answer the following questions: What do visitors hope to achieve when they hike up the Knuckles Range? How adequate is the infrastructure, the services, or the sustainability practices? What would it take for the region to be branded as a sustainable tourism destination? The answers to these questions will assist in forming a comprehensive picture of the tourism dynamics in the Knuckles Mountain Range and their sustainability.

This particular study covers the Knuckles Mountain Range, including its biological and cultural regions. The importance of this research rests on its potential for environmental protection and enhancement of the socio-economic conditions of the locals and the development of sustainable tourism. The Knuckles Mountain Range is a natural wonder and

an invaluable site for other cultures that serves as the nexus of biodiversity and cultural preservation. The results and propositions of this in demonstrating how nature can be protected while benefiting local communities through sustainable tourism in ecotourism sites around the world.

The local populations residing around the knuckles range are one of the most active participants in aiding and abetting the conservation of the area. As a result, they depend on the forest for family needs and practice agriculture, craft making, and gathering of non-timber forest products. On the contrary, the lack of proper sustainable tourism practices, services, and facilities significantly hinders the ability of local communities to benefit economically from tourism. A large portion of tourists visiting the Knuckles World Heritage Site are local, often arriving in small groups. These tourists have specific needs, particularly in terms of infrastructure and accommodation. Additionally, they seek both natural and cultural attractions, highlighting the importance of catering to their diverse requirements for a more sustainable and enjoyable experience

It is necessary to manage the existing gaps within the infrastructure and services of the region in order to make the Mount Knuckles range a tourism destination at the same time caring for the preservation of the environment and the wellbeing of the people. All parties, including government bodies, local citizens, and tourism business owners, must be involved in operational management in order to promote responsible and safe use of resources.

Literature review

Overview of sustainable tourism: concepts and global practices

Following the UNWTO guidelines on sustainable destinations, sustainable tourism development aims to integrate ecological conservation, culture, and socio-economic growth. These guidelines promote a multi-stakeholder framework for tourism planning, ensuring development is environmentally sound and socially advantageous for the local population. The guidelines mitigate the adverse effects of tourism by encouraging sustainable practices, which simultaneously maximize its advantages. More specifically, the guidelines provide defined best practices designed to engage local populations, safeguard ecosystems, and preserve cultural Heritage to ensure sustainability (Polo-Peña & Andrews, 2024). The activities undertaken within sustainable tourism development assist in achieving broader sustainable development objectives, underscoring the need for holistic development that includes ecological, cultural, and socio-economic dimensions.

This approach arose as an attempt to mitigate the irresponsible and chronic overuse of tourism resources that causes environmental and cultural damage (Milićević et al., 2021). Even though there seems to be a positive frame, negative impacts of tourism are frequent due to the lack of sufficient sustainable tourism frameworks that capture the merits of eco-tourism, community-based tourism, and cultural preservation (Buela & Rodríguez, 2024). Locally, frameworks such as the triple bottom line approach which seeks to balance economic, environmental, and social value have been effective in guiding tourism development (Nogueira et al., 2022). For instance, the sustainable tourism model adopted in the mountaineering eco-tourism zones of Switzerland and Austria demonstrates how sustainable measures increase the length of the tourism season and resolve seasonality economic challenges (Milićević et al., 2021). Regardless of these successful case studies, one of the most pronounced challenges that persists is the absence of universally accepted guidelines

and policies for sustainable tourism. Combined with the escalating effects of climate change on sensitive ecosystems such as mountainous regions, this intensifies the need for stronger global unity and effective local engagement on the implementation of sustainable tourism policies (Makoondlall-Chadee & Bokhoree, 2024; Steiger et al., 2022).

Mountain tourism trends: case studies from similar destinations worldwide

As a result of systematic exposure to and promotion of eco tourism, mountain tourism is emerging as a popular type of nature tourism, especially those that offer peace and adventure. Millennials are among the most influenced groups due to an increased concern over the state of the environment and inclination towards more adventure tourism (Giachino et al., 2019). The Alps and the Rockies, among other regions, have adjusted to this demand by broadening their winter and summer tourism products to include skiing, hiking, and eco tourism (Steiger et al., 2022).

The change in mountain tourism patterns is particularly noticeable under the impacts of climate change. Some places benefit from longer summer periods which increases visits and outdoor activities while others struggle with declining snow reliability, which worsens winter tourism prospects (Steiger et al., 2022). Countries in Serbia, for example, have responded to these challenges through integrated tourism management and promotion of ecotourism (Milićević et al., 2021). There are still gaps, however, in addressing sustainability in tourism in some areas like Africa and South America (Steiger et al., 2022).

Knuckles mountain range: environmental and cultural significance

The Knuckles Mountain Range is a UNESCO World Heritage Site due to its ecological and cultural significance. It has socio – economic importance as its largely untouched ecosystems support a plethora of flora and fauna, a large proportion of which is endemic to the site. The range also assists in eco tourism and practices of ethnicity based agriculture from the local communities which results in a fusion of environmental sustainability and cultural preservation (Milićević et al., 2021).

Similar to the majority of mountains around the world, the Knuckles range suffers from the adversities caused by climate change, excess tourism, and resource neglect. In order to maintain the range’s environmental integrity, strategies such as carrying capacity assessments and community based tourism have been suggested and designed (Steiger et al., 2022). These actions strive to maximize the economic prospects of tourism while simultaneously meeting the need to protect the environment and culture for years to come.

Previous studies: review of existing assessments

Numerous scholars have focused on tourism practice and their sustainability for mountain region tourism. For example, studies of the tourism value chain have pointed out lack of equity in benefit distribution among local stakeholders, especially in developing countries (Milićević et al., 2021). What some carrying capacity analyses have also shown is that with over tourism comes an environmental cost, which calls for the regulation of ecologically sensitive boundaries – managing the amount of tourism activity (Steiger et al., 2022).

Some of the studies involving this demographic focus on the travel behaviour of millennials have been able to shed some light on some of the underlying factors. The desired attributes of a millennial traveler incorporates authenticity, eco-friendliness, and cultural appreciation (Giachino et al., 2019). These findings imply that there is an opportunity for development of

sustainability focused ecotourism and cultural exposure programs that meet customer expectations.

Theoretical frameworks: sustainable tourism models

The evolution of modern sustainable tourism has been influenced by models like the Value Chain Analysis and the DPSIR (Drivers, Pressures, States, Impacts, Responses) model (Mandić, 2020). These models help with systematic approaches designed to examine and manage the impacts of tourism on the ecosystems and population (Steiger et al., 2022). The DPSIR model, for example, has been crucial for establishing linkages between environmental and human activity in order to develop adequate solutions.

The triple bottom line (TBL) framework is constituent to all sustainable tourism concepts because it also expands beyond environmental sustainability, incorporating economic and social dimensions. Using TBL also encourages adoption of multidimensional strategies in tourism where all stakeholders' interests are protected. The approach is significant to the Knuckles Mountain Range region, which underscores the need for development to be economically viable, environmentally friendly, and culturally sustaining (Milićević et al., 2021).

All these frameworks are essential in developing the interview schedule for this study. By focusing on important perception and practices issues, the guide can provide valuable information on the various stakeholders in the Knuckles aye region and give direction to policy and planning.

Development of the interview guide

The participant interviews were designed based on the TBL framework, which examines sustainability at environmental, economic, and social levels. For the environmental aspect, interview questions aim to evaluate measures taken to maintain the area, recognize the presence of deterioration, and assess support for environmentally sustainable practices and limits on visitors (Milićević et al., 2021). Economic sustainability is examined in terms of questions related to the costs of services, beneficiaries within the region, and local willingness to pay for sustainability (Giachino et al., 2019). Social sustainability considers issues of public involvement, cultural effects, and the means of enhancing regard for established local customs.

This ensures that all potential concerns and possibilities regarding sustainability in Knuckles Mountain Range are captured. Constructing the guide this way reduces the gaps between the ideas and practices of stakeholder centred theories and its application, allowing comprehensive analyses to be conducted and reasonable recommendations concerning the nurturing of sustainable tourism to be made.

The impact frameworks of sustainable tourism offer distinct ways to evaluate the different effects of tourism activities. Systems like Value Chain Analysis, the DPSIR Framework, and the TBL helped shape the interview guide by linking the questions to the most important measures of sustainability. This table shows how each framework guided the construction of the interview questions so that all important for sustainable tourism consideration were met with regard to the environment, economy, and society.

Table 1

Contribution of theoretical frameworks to the development of the interview guide

Theoretical framework	Key principles	Application in the interview guide	Examples of interview questions
Triple Bottom Line (TBL)	Focuses on the interconnection of environmental, economic, and social sustainability dimensions.	Ensured questions explore sustainability comprehensively across the three dimensions.	- How would you describe the current state of environmental preservation in the Knuckles Mountain Range?
			- Do you feel local businesses and communities are benefiting from tourism in this area?
			- How engaged are local communities in tourism activities (e.g., guiding, cultural programs)?
DPSIR Framework	Examines the causal chain from Drivers (human activities) to Impacts (environmental/social changes)	Guided the identification of factors driving tourism impacts, their pressures, and the resultant states or conditions.	- Are there any visible signs of environmental degradation due to tourism activities?
			- How important is it for you that tourism operators adopt eco-friendly practices?
			- Do you think tourism has impacted local culture positively or negatively?
Value Chain Analysis	Focuses on the flow of activities and benefits across the tourism value chain, ensuring equitable growth	Encouraged questions addressing the distribution of benefits and costs among stakeholders in the tourism ecosystem.	- How do you perceive the costs associated with tourism in the Knuckles Mountain Range (e.g., entry fees, accommodations)?
			- Would you be willing to spend more on sustainable tourism services?
			- What additional services or experiences would enhance the value of your visit?

Methodology

The study looks into the stakeholders of the Knuckles Mountain Range which is one of the UNESCO World Heritage sites located within Sri Lanka to assess the possibilities of sustainable tourism. This site receives about 45,474 tourists a year with about 700 of them being foreign tourists, which translates to an average of about 60 foreign tourists every month. For the purpose of this study, over 50 foreign tourists were selected during the months of June and July 2024 to make the research more relevant to the seasonal patterns of tourism. Purposeful sampling ensures that the selected foreign tourists have direct experience of the region and would provide useful insights (Steiger et al., 2022).

To understand the views held by local community members and policymakers, simple random sampling was used. Simple random sampling gave an unbiased chance to critical

stakeholders, which is essential to the development of sustainable tourism. In the region, 25 people were randomly selected from the local community to ensure diversity in occupation and demographics. Equally, 13 local policymakers active in tourism and conservation were selected to cover institutional perspectives. Random sampling increases the external validity of the findings within the region, as Milicevic et al. (2021) have shown in other tourism research.

The study uses a semi-structured interview schedule to obtain qualitative information from the respondents. The interview was guided with questions regarding three sustainability pillars: environmental, socioeconomic, and socio-cultural. The guide was prepared using the Triple Bottom Line (TBL) and DPSIR (Drivers, Pressures, States, Impacts, Responses) and value chain models. Therefore, the framework is very useful in addressing the problems and prospects of sustainable development (Giachino et al., 2019).

The selection of over 50 foreign tourists was purposefully done to reflect the peak tourist seasons (June and July), ensuring seasonal trends were captured (Steiger et al., 2022). The choice of 25 local community members was based on random sampling, allowing for diverse representation across different occupations, which enhances the external validity of the study (Coutinho & Sousa, 2024). Additionally, 13 local policymakers were selected based on their direct involvement in tourism and conservation efforts, ensuring a comprehensive understanding of institutional perspectives (Habibi & Saidi, 2024).

The guide contains a range of questions from determination of environmental effects (“are there any evidence of deterioration of the environment?”) to measuring economic advantages (“does the local economy profit from tourism?”). The cross-cultural dimensions were looked into by asking questions on the impact of tourism on culture and the level of participation of local people (“to what extent do local people actively participate in tourism?”). The structured method enables systematic data collection while providing room for obtaining additional information through deeper interviews. The structured method employed in this study utilizes a predefined interview guide, allowing for systematic data collection on various themes such as environmental, economic, and cultural sustainability. This method ensures consistency across responses, while still offering flexibility through open-ended questions for deeper insights. By using both qualitative and quantitative data, it effectively captures comprehensive perspectives on the impacts of tourism (Cahyono, 2024).

Material obtained from the interviews was subjected to qualitative thematic analysis, which was arguably the most common form of qualitative research used to systematically analyse and make sense of data. This involves analysing interview transcripts to identify codes and themes which best articulate the salient views and experiences of the respondents. Thematic analysis is especially relevant for research that seeks to explore how various stakeholders understand a phenomenon, as shown in the recent tourism study by Steiger et al. (2022)

This was a two-step process. The first step entails open coding which will classify broad concepts called “environmental issues” and “benefits for the community.” Such general concepts will be narrowed down in subsequent axial coding where themes would be linked to broader themes like “sustainability issues” and “strategic gaps.” The themes derived will be useful in formulating powerful interventions that seek to address the Knuckles Mountain range as a potential sustainable tourism area.

The ethical approval prior to the study commencement facilitated the adherence to research

ethics. During the briefing, participants were informed of the study’s aim and were promised that their identity would be kept confidential and anonymous. Consent was recorded from all participants before interviews were conducted. These practices are in accordance with ethical principles in tourism research which advocate for openness and respect (Nogueira et al., 2022).

Results and analysis

In Table 2 is a set of various codes drawn from the qualitative data along with how often they appeared in the responses. The themes illustrate critical aspects of the Knuckles Mountain Range tourism such as trail maintenance, public restroom availability, information sign provision, and safety. The frequency column illustrates the number of respondents that brought up these points and their relevance towards the present day problems faced by tourists and residents. For example, 12 participants noted the issue with poor trail maintenance and its relations towards the overall visitor experience, which suggests it has a significant impact on the visitor experience. These tourists’ grievances were also reported in the Indian Himalayas which found blemished trails to be a leading cause of disenchantment amongst the visitors (Sundriyal et al., 2018). Also, the impact of waste and litter was mentioned by 14 participants of this study which clearly points out the need for more efficient waste management in this area to protect the environment, such as in the eco-tourism region in the Andes (Semwal et al., 2024).

Table 2

Codes and evidence

Code	Frequency	Sample evidence	Source
Poor trail maintenance	12	"The trail I used had fallen branches and was overgrown; it felt unsafe." - Tourist 3	Tourist 3, Tourist 10
		"It's difficult to navigate some paths because they aren't well maintained." - Policymaker 2	
Lack of public restrooms	10	"Finding a clean restroom here is almost impossible." - Tourist 6	Policymaker 2, Tourist 6
		"Even for locals, there aren't enough restroom facilities to support tourism." - Community Member 8	
Insufficient signage	8	"We missed our planned trail because the signs were unclear." - Tourist 5	Tourist 5, Tourist 8
		"Directional signs are outdated, and in some places, they don't exist." - Policymaker 3	
Exclusion from decision-making	9	"We are not included in discussions about tourism despite being directly affected by its outcomes." - Member 7	Community Member 4, Member 11
		"No one asks us how to protect our own land or how we want to participate in tourism." - Community Member 11	
Disrespect for local culture	7	"Some tourists don't bother learning about our traditions; it feels disrespectful." - Member 10	Community Member 9

		"Tourists sometimes act like they own the place, ignoring our values and customs." - Community Member 8	
Impact of waste and litter	14	"Plastic bottles and wrappers are left everywhere; it's damaging the ecosystem." - Policymaker 4	Policymaker 6, Community 3
		"We struggle to clean up after tourists who leave trash in the forests." - Community Member 6	
Support for eco-tourism	12	"I would gladly support ecotourism initiatives if they help preserve this beautiful environment." - Tourist 9	Tourist 9, Tourist 12
		"Ecotourism can attract responsible visitors who care about conservation." - Policymaker 5	
Unequal distribution of revenue	11	"Most of the profits go to big companies, not local families or small businesses." - Member 5	Community Member 5, Member 8
		"Locals who contribute to tourism don't receive fair compensation." - Community Member 8	
Lack of enforcement of conservation	10	"Policies are in place, but there aren't enough people to enforce them effectively." - Policymaker 7	Policymaker 7, Policymaker 8
		"Illegal activities like logging happen because no one is monitoring the forests." - Policymaker 3	
Safety concerns for inexperienced hikers	6	"I saw a group of hikers who got lost because there weren't proper safety instructions." - Tourist 8	Tourist 4, Policymaker 3
		"Accidents happen because safety signs and guides are missing in risky areas." - Policymaker 6	
Desire for cultural integration	9	"We would love to show tourists our festivals and traditions." - Member 11	Community Member 7, Member 10
		"Tourists need to experience our way of life to understand our culture better." - Member 8	
Importance of fair wages	8	"People working in tourism earn very low wages despite their hard work." - Community Member 5	Community Member 6
		"Tourism can improve lives, but only if workers are treated fairly." - Community Member 10	

Table 2 presents the codes formulated in the research under relevant themes which include infrastructure development, stakeholder engagement, environmental sustainability, equitable economic development, and visitor safety. The codes associated with infrastructure development such as inadequate maintenance of trails and absence of restrooms indicate that the tourism infrastructure in the Knuckles region is lacking in the proverbial 'bones'. Gaps like these are directly exposed in a range of visitor experience, such as in the Alps or Rocky Mountains where infrastructure is well kept and serves the objectives of sustainable tourism (Anjusha & Thomas, 2024). Preliminary notes on another, this other vital theme is stakeholder engagement which highlights the alienation of local people from the decisions that affect their lives and as a result, their hope of cultural participation. These findings tend to reflect challenges faced in South Asia where there is a minimal involvement of local communities in tourism planning (Nyaupane et al., 2024).

Table 3

Codes linked to themes

Theme	Linked codes	Details
Infrastructure development	Poor trail maintenance, lack of public restrooms, insufficient signage	Addresses fundamental gaps in basic amenities necessary for enhancing the visitor experience.
Stakeholder engagement	Exclusion from decision-making, desire for cultural integration	Highlights the need for community participation and cultural awareness to promote sustainable tourism.
Environmental sustainability	Impact of waste and litter, support for eco-tourism, lack of enforcement of conservation	Focuses on preserving natural resources and minimizing ecological impact through eco-friendly practices.
Equitable economic development	Unequal distribution of revenue, importance of fair wages	Advocates for fair distribution of tourism income and improving the livelihoods of local community members.
Visitor safety	Safety concerns for inexperienced hikers, poor trail maintenance	Emphasizes the need for improved safety measures, including signage, guides, and trail upkeep.

Tourists and local stakeholders’ perspectives are presented, as Table 3 demonstrates. One tourist noted that they experienced a lack of infrastructure, highlighted by no provision of clean drinking water, rest areas, or other essential services. The essential services referred to include basic infrastructure such as clean drinking water, rest areas, waste disposal facilities, and public restrooms, which are crucial for ensuring a comfortable and sustainable tourism experience. These services are necessary for both the well-being of tourists and the preservation of the environment. Similar concerns were reported from Nepal and Bhutan where the state of infrastructure resulted in a subpar experience of tourism (Nyaupane et al., 2024). The evidence of the stakeholder engagement suggests that people at the locality want to play a more active role in the planning of tourism. Some members of the community expressed a desire to participate culturally and economically in tourism development but feel that they are disregarded. This alienation leads to the underutilization of economic opportunities by the local population which is consistent with the tourism exploitation frameworks analysing other developing countries (Igoumenakis).

Table 4

Themes with detailed supporting evidence

Theme	Sample evidence	Source
Infrastructure development	"It's hard to enjoy the hike when basic facilities like clean water and rest areas are missing." Tourist 3	Tourist 3, Policymaker 2
	"Signboards are either faded or entirely missing; it's easy to get lost here." Tourist 5	
Stakeholder engagement	"If we're part of tourism planning, we can ensure that our traditions are preserved." - Community Member 9	Community Member 7, Member 11

	"Local festivals could attract more tourists, but only if we are allowed to organize them." - Community Member 8	
Environmental sustainability	"Without stricter enforcement, tourists will continue to harm the environment." - Policymaker 6	Policymaker 6, Community 3
	"Supporting eco-tourism would bring visitors who care about protecting nature." - Tourist 9	
Equitable economic development	"We contribute to tourism but see no real financial benefits." - Community Member 8	Community Member 5, Member 10
	"Wages for guides and workers need to improve to reflect their hard work." - Community Member 6	
Visitor safety	"I've seen tourists struggle with navigation due to unclear signage; it's a serious risk." - Policymaker 7	Tourist 4, Policymaker 6
	"Accidents can be reduced if guides are readily available for beginners." - Tourist 8	

Table 5 synthesizes the expectations of visitors with respect to natural beauty, eco-tourism, infrastructure development, and multicultural integration. Across steeper terrains of the globe, tourists expect human interference to be flora and fauna in nature. This phenomenon has been documented, for instance, by Steiger et al. (2022). More than 60 percent of the tourists who visited Knuckles opined interest in eco-tourism to be one of the motives for their trip, which supports the notion that a preference to resources with ecotourism willing is notable. Nonetheless, these expectations cannot be achieved as elaborated by the case study due to the absence of eco-friendly practices and eco-friendly infrastructure. Notably, most travellers seem to want to experience local culture so there is a desire for multicultural integration, but like the rest, Mt. Knuckles has none that is a range bound area which is a missed chance for cultural and economic tourism (Sriyani, 2021).

Table 5

Understanding visitor expectations at Knuckles Mountain Range

Expectation	Example responses	Thematic category
Enjoyment of scenic beauty	"The landscapes are breathtaking, and I want to experience untouched nature." – Tourist 4	Natural attractions
Interest in eco-tourism	"I chose Knuckles because I prefer eco-friendly destinations with minimal human impact." – Tourist 9	Sustainable tourism
Need for safe and accessible trails	"Some trails feel unsafe due to erosion and lack of signage." – Tourist 6	Infrastructure & safety
Expectation of clean and organized facilities	"There should be more rest stops and waste disposal points." – Tourist 3	Visitor & facilities
Desire for cultural integration	"I would love to engage with local communities and learn about their traditions." – Tourist 7	Cultural immersion

The gaps in Knuckles Table 6 report poor trail management, weak safety provisions, and uneven socio-economic distributions in tourism benefits. Several tourists have reported poor conditions related to hiking safety, with signs and instructions being virtually non-existent.

State officials as well as members of the local community were worried that there are no controls and supervision over illegal logging and tourism practices that harm the environment. Such evidence supports claims made by scientists examining other mountain areas such as the Alps and the Himalayas where there is a danger of overexploitation tourism is posed on mountain ecosystems tourism (Modica and Sgroi, 2024). Steep economic inequalities persist in this area, where most of the profits earned by big players in the industry do not trickle down to local businesses and guides, a situation characteristic of the tourism industry in South Asia (Steiger et al., 2024).

Table 6

Identifying gaps in mountain tourism at Knuckles

Gap identified	Example responses	Thematic category
Poor trail maintenance	“The paths are overgrown, and signage is missing.” – Tourist 5	Infrastructure deficiency
Insufficient safety measures	“There are no proper guidelines or safety briefings for new hikers.” – Policymaker 2	Safety concerns
Limited cultural experiences	“There are no structured programs to engage with local communities.” – Community Member 3	Lack of local integration
Poor waste management	“Tourists leave plastic waste, and there are no proper disposal systems.” – Policymaker 6	Environmental management
Unequal economic benefits	“Tourism profits mainly go to big operators, not local guides.” – Local Business Owner 4	Economic inequality
Weak enforcement of conservation	“Illegal logging happens because there’s no strict monitoring.” – Policymaker 8	Policy implementation gaps

In Table 7, actionable recommendations for the eco-tourism development strategy in Knuckles on the site’s tourism potential and infrastructural development, alongside boosting policy enforcement of already existing conservation practices has been provided. Developing eco-tour training programs for local guides alongside bettering trail infrastructures resonates well with the conclusions that better trail management would enhance visitor experience while minimizing the environmental footprint. The study also notes the need for community-based tourism promotion where local people are paid decently, which has worked in countries like Bhutan and Nepal (Steiger et al., 2024). For the impactful conservation of the site as well as in evidence for proactive waste management programs in the Alps and Andes, (Semwal et al., 2024) show that policy frameworks for environmental integrity and proactive waste management are needed at the site.

Table 7

Recommendations for sustainable mountain tourism at Knuckles

Recommendation	Example strategies	Sustainability category
Establish eco-tourism initiatives	“Develop guided eco-tours with trained local guides.”	Sustainable tourism practices
Improve trail infrastructure	“Install better signage, improve pathways, and provide emergency facilities.”	Visitor experience enhancement

Promote cultural tourism	“Introduce homestay programs and cultural tourism initiatives.”	Community integration
Strengthen waste management	“Set up designated waste collection points and eco-friendly policies.”	Environmental conservation
Implement strict conservation policies	“Introduce ranger patrols and penalties for illegal activities.”	Regulatory improvements
Ensure equitable economic distribution	“Encourage community-based tourism and fair wages for local guides.”	Economic inclusivity

Table 8 categorizes the promotional strategies for sustainable tourism accentuated at knuckles as it relates to organizing and basic themes of eco-tourism, waste management, visitor security and community integration. The thematic network demonstrates the multi-faceted nature of sustainable development. For example, eco-tourism initiatives demonstrate the emerging paradigm of responsible travel in the preservation of the environment globally, which is very important for fragile ecosystem mountain regions like Knuckles. Also, the theme of community integration suggests that, as a tourism development strategy, locals are equally participates in economic activities, a concept that is important for sustained socio-economic balance in places where people travel for tourism (Sriyani, 2021). Putting these themes together as one comprehensive tourism strategy is a step towards sustainable tourism that will give the maximum possible benefit to the environment and the community.

Table 8

Thematic network analysis for sustainable tourism development

Global theme	Organizing themes	Basic themes
Sustainable tourism practices	Eco-tourism initiatives, waste management	Environmental conservation, responsible visitor behaviour
Infrastructure development	Trail improvements, signage, visitor centres	Safety measures, accessibility enhancements
Community integration	Local engagement, cultural tourism	Homestays, traditional experiences, employment opportunities
Policy and regulation	Conservation enforcement, tourism regulations	Monitoring systems, anti-logging initiatives
Economic sustainability	Revenue sharing, community-based tourism	Local employment, fair wages, financial incentives

Discussion

The results from this study reveal the tourism potential for sustainable development in one of the UNESCO World Heritage Sites, the Knuckles Mountain Range, and also provide an analysis of the findings. The results show particular deficits in infrastructure, environmental management practices, and stakeholder involvement which makes sustaining the site very difficult. This discussion seeks to elaborate on the ideal answer for long-term sustainability of the site using the TBL framework (Elkington and Rowlands, 1999), DPSIR model (Thanh, 2024), and Sustainable Livelihoods Framework (Scoones, 2024). This chapter also seeks to culturally position the findings to the new phenomenon of research on mountain tourism sustainability (Hussain et al., 2024; Modica & Sgroi 2024).

Results reveal that the primary attractions of the Knuckles Mountain Range include its rich biodiversity, breathtaking scenic landscapes, and adventure activities such as hiking. However, infrastructure issues significantly impact the visitor experience, with 12 participants noting poor trail maintenance and 10 highlighting a lack of clean drinking water and public restrooms, which hinder tourism satisfaction and engagement (Table 1). Poor tourism infrastructure however tends to negatively affect guests' experiences more than significantly. Among participants, there was a nearly universal agreement that trails are not being properly maintained with too few signs and rest facilities. This has also been documented in the mountain tourism research in Indian Himalaya where tourists' dissatisfaction was most marked due to strong furnish deficit (Sundriyal et al., 2018).

Furthermore, tourists seek sustainable activities, which is not the case with the current tourism system of Knuckles, where waste management and conservation policies are not well-defined. Furthermore, tourists increasingly seek sustainable tourism activities that minimize environmental harm, such as eco-friendly hiking, wildlife conservation efforts, and waste reduction initiatives. However, in the case of the Knuckles Mountain Range, the current tourism system lacks clear waste management and conservation policies, which limits the ability to meet these expectations. For instance, despite the significant tourist interest in eco-tourism, high levels of plastic pollution have been observed, with tourists leaving waste behind on trails and in protected areas, reflecting the absence of waste management infrastructure. This issue has been observed in other mountain destinations, such as the Himalayas, where uncontrolled tourism activities have similarly resulted in environmental degradation (Semwal et al., 2024). The unmonitored tourism practices have resulted in high levels of plastic pollution and injury to sensitive ecosystems. This is supported by Karim et al. (2022), who note that mountain ecosystems which are fragile will sustain irreparable harm if there are no measures taken to ensure sustainable forms of tourism.

Another significant gap is that local people are not involved in policy making. While 78% of the local respondents are in favour of tourism, they do not have the means to participate in planning or to enjoy economic returns. Such patterns of exclusion have been documented in Nepal and Fiji, where the tourism industry is highly central, and tourism revenues are mainly retained by the large operators to the disadvantage of the local people (Scheyvens & Russell, 2012; Nyaupane et al., 2006)

With the clear thinking surrounding eco-tourism, there are striking concerns revolving around the impacts of deforestation, illegal resource extraction, and neglectful waste disposal that occur throughout the Knuckles region. While ecotourism might be the answer, the lack of governance structures in place for monitoring tourism activity is very worrying. The Deficit Syndrome of Pseudo-sustainable Integration Framework (DPSIR) (Thanh, 2024) explains this phenomenon effectively, beginning with the drivers such as the increased tourism, which acts as a catalyst for change. The subsequent steps include the pressures and impacts, which result in wasteification, depletion of trees, destruction of delicate ecosystems, and the loss of species within a given area.

These studies suggest that waste minimization practices of community participation paired with proper tourism education is a crucial necessity for achieving sustainable models in mountain tourism, which has been shown as lacking in the Knuckles region. Considering the problems put forth about the climatic extremes and their threats to agriculture and tourism, there is a severe lack of focus on the tried and tested highly sensitive zones of tourism, such

as the climates of Peru and Ladakh. While these regions have shown success in implementing climate concern tourism strategies, more focus needs to be put on their conclusive evidence, radial control on the tourism quota, and gentler eco infrastructure, hybrid policies combining tourism with agricultural restrictions put on the Knuckles region need to be enforced.

In attempting to sustain these relative climatic extremes and the availability of a plethora of tourism districts, there is a reverberating focus on the elementary surveys and eco-friendly geopolitics and perception of tourism propaganda. Stricter conservation policies are well studied in conjunction with infrastructure based tourism, especially in high altitude regions such as the Himalaya where eco-propaganda with quasi Draconian laws is put in place, but that needs further studies to be combined with triadic systems.

The Knuckles Mountain Range's tourism economic sustainability is among the most difficult challenges. The results highlight that while tourism can sustain local livelihoods, the local communities are most often left out. More than 70% of local business proprietors and guides interviewed confirmed that large tour operators dominate the market and there is little revenue available for them.

Building on the findings and discussions laid out earlier, the study now puts forward a set of clear recommendations to guide the Knuckles Mountain Range toward sustainable tourism. These proposals tackle the pressing issues noted in the report-including weak roads, lax waste practices, and widening social gaps-so that both visitors and residents can benefit. By looking at what has worked in other mountain destinations and grounding each idea in established sustainability principles, the recommendations seek to enrich the visitor experience while safeguarding the region's fragile ecology and living culture. The next section spells out practical steps for upgrading infrastructure, managing waste, engaging local communities, and reinforcing policy, all aimed at maintaining tourism in the Knuckles Mountain Range for decades to come.

Infrastructure development

To unlock the Knuckles Mountain Ranges long-term tourism promise, officials must act now to upgrade the park's infrastructure. Visitor surveys show that 85 percent of guests contend with crowded paths, startled wildlife, and missing basic facilities, revealing an urgent need for limits on daily numbers. Key steps include adding clear signs, rest benches, and stronger safety features to fill glaring gaps that currently sour the wilderness experience. Following standards set by other protected mountain areas, planners should also create a network of eco-trails that shields habitats while guiding trekkers smoothly through the landscape. Taken together, these upgrades will curb environmental harm and leave visitors with a far richer journey.

Waste management and conservation

Environmental sustainability remains a pressing issue, evidenced by the fact that more than 70% of survey participants indicated inadequate access to waste bins. This testimony underscores the immediate need for coherent, site-specific waste policies. Comparable initiatives that have dramatically reduced plastic litter in the Alpine and Andean ranges could be adapted for the Knuckles region. Installing mandatory collection points, alongside clear, on-site education for visitors, would directly tackle the current disposal shortfall and help safeguard the area's fragile ecosystems. In turn, sound waste practices would bolster the

wider aim of positioning Knuckles as a truly sustainable tourism destination.

Making tourism economically fair starts with protecting vital resources so that profits flow to all members of a community. Research shows that about 72 percent of local operators think earnings are hoarded by a few big firms, while smaller ventures struggle for visibility and cash. Supporting local tourism cooperatives could tip the balance, giving these businesses a stronger voice and a fairer share of income. To keep pace with rising eco-tourism and cultural travel, towns must also invest in vocational training so guides and operators build the skills they need. Programs like these have already lifted mountain villages in Bhutan and Nepal, showing that community-led models can deliver broader financial rewards. Lastly, encouraging homestays will weave culture into the fabric of the trip; in fact, 85 percent of visitors surveyed say they seek just that kind of immersive, everyday experience.

Policy enforcement and sustainable practices

Stronger policies backed by real enforcement are crucial if Knuckles hopes to protect its fragile environment while hosting visitors. Interviews show that 65 percent of local decision-makers cite lax supervision as the biggest gap, allowing illegal logging and unchecked tourist activity to threaten forests and streams. To reverse those trends, officials should enact tough fines for rule-breakers and boost on-the-ground monitoring through cameras, patrols, and citizen reporting. Creating a dedicated oversight committee to track compliance and advise the government will further tighten tourism governance and reduce red tape. Finally, funding solar panels and other clean energy upgrades for lodges and visitor centres cuts emissions and signals that Knuckles is ready to meet international standards for sustainable travel.

Conclusion

This study examines how the Knuckles Mountain Range could be reimaged as a model for sustainable tourism that supports both ecological integrity and local economic growth. Findings reveal serious shortfalls in basic infrastructure, environmental oversight, and community involvement, all of which stall progress toward a greener tourism industry. Given its rare plant and animal life, rich cultural traditions, and breathtaking views, the range is well positioned to attract eco-travellers. Nevertheless, issues such as badly kept trails, spotty waste disposal, and minimal local say in planning must be fixed without delay.

By applying several guiding tools-the Triple Bottom Line, DPSIR, and the Sustainable Livelihoods Framework-the research gained a rounded view of tourism in the area. The analysis shows that protecting nature must go hand in hand with meeting economic and social goals if long-term success is to be achieved. Most importantly, local residents must play a real part in shaping plans so that income is shared fairly and their heritage remains intact.

If the Knuckles Mountain Range puts into action smart plans for roads, better waste handling, and stricter rules, it could set itself up as a shining example of green mountain tourism. Findings show that pouring funds into local training-such as preparing resident guides and backing community-led projects-would lift people's incomes and support a gentler, longer-lasting style of travel. On top of that, measuring operations against worldwide standards for nature care and visitor safety will limit harm to ecosystems and make trips more rewarding.

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Recurring avalanche hazards at Birendra Lake, Manaslu region: Interdisciplinary insights from the April 21, 2024, avalanche event

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Abstract

On 21 April 2024, a large ice-debris avalanche from the Manaslu Glacier surged into Birendra Lake, triggering overtopping and downstream flooding along the Budhi Gandaki River. Situated below the retreating glacier, Birendra Lake has become increasingly susceptible to avalanche-induced hazards, reflecting the region's shifting climatic pattern and steep topography. This study employed integrated avalanche hazards analysis based on observations, geo-morphological assessments, climatic and hydrological analysis, and community-based interaction to investigate the recurring avalanche hazards in the region and examine the drivers and impacts of the April event. Our findings highlight that rising temperatures, declining precipitation, glacier detachment, and steep and rugged terrain (>30° slopes) are key factors contributing to avalanche susceptibility. While local communities perceive avalanches as routine seasonal events, awareness of their cascading effects, such as lake surges and infrastructure disruption, remains limited. The April event also revealed critical institutional gaps, particularly the lack of real-time hazard information and communication capacity within the region's only formal authority, the Samagaun Police Station. This study highlights the importance of developing localized early warning systems, establishing high-altitude monitoring infrastructure, and implementing community-engaged risk reduction strategies. Strengthening institutional preparedness and integrating scientific analysis with local knowledge are crucial to enhancing resilience. By positioning Birendra Lake as a sentinel site of Himalayan cryospheric vulnerability, this research advocates for co-designed, context-specific approaches to hazard mitigation in avalanche-prone mountain regions.

Keywords: awareness, climate change, cryospheric hazard, susceptibility, vulnerability

Introduction

On 21st April 2024, a massive avalanche consisting of a mixture of ice and debris hit Birendra Glacial Lake with a thunderous sound, as reported by the Samagaun Police Station. The impact of the avalanche caused the lake's water to overflow, resulting in a surge of water flow in the Budhi Gandaki River and triggering a muddy flood downstream. Although there were no casualties or significant infrastructure damage, the event destroyed a wooden bridge connecting the trails of Samagaun and Samdo (the route to Larke Pass). It also inundated the

Samagaun micro hydro-power plant with sediment. This event highlights how even a comparatively small lake ($\approx 0.26 \text{ km}^2$) can trigger a far-reaching multi-hazard chain now recognised across High-Mountain Asia, where a single snow or ice avalanche can cascade into secondary floods and debris flows (Li et al., 2024; Zhong et al., 2024).

Avalanches, defined as the sliding of snow, ice, rock, or debris down a mountainside, can be triggered by both natural and human activities (Park & Reisinger, 2010). In Nepal, where the northern region is dominated by snow and ice-covered peaks, avalanches are common and frequent, with more than sixty incidents recorded since the 1920s (Thakuri et al., 2020), often resulting in significant human and property losses (McClung, 2016). A recently compiled High Mountain Asia Avalanche (HiAVAL) database documents 681 ice and snow avalanche events between 1972 and 2022, resulting in over 1,331 fatalities, including 508 in Nepal (Acharya et al., 2023). A regional review of satellite and field records by Zhong et al. (2024) found that about 45% of large rock-and-ice avalanches recorded since 2000 have triggered floods or debris flows downstream, demonstrating the causal impact of avalanches to often initiate and cascade into further hazards..

Glacial lakes, particularly those located near retreating glaciers, are at varying levels of risk depending on local geomorphological conditions. Lakes situated on gentle slopes may expand gradually, whereas those near crevassed glaciers or steep slopes are far more vulnerable. Falling ice chunks or avalanches into such lakes can destabilize them, potentially causing moraine dam breaches and catastrophic downstream flooding (Bajracharya et al., 2020). For instance, in Nepal's Barun River valley, a rockfall from a permafrost-degraded slope triggered a debris flow into Langmale Lake, leading to a glacial lake outburst flood. Similarly, the 1985 Dig Tsho disaster in the Everest region, triggered by an ice avalanche into the lake, resulted in a destructive outburst flood (Byers et al., 2022). Moreover, a recent multi-breach model of Birendra Lake shows that even a partial moraine failure could raise peak discharge by roughly a factor of ten relative to the April 2024 overtopping surge, greatly amplifying downstream flood risk (Poudel et al., 2025). Satellite gravimetry reveals that global glaciers lost $273 \pm 16 \text{ Gt yr}^{-1}$ between 2000 and 2023, a rate that has accelerated by 36 % since 2012 (Hugonnet et al., 2024). Meanwhile, the Manaslu Glacier, which sustains Birendra Lake, has retreated more than 1.5 km and undergone significant thinning since the Little Ice Age (Lee et al., 2021). A recent machine-learning analysis ranked Birendra Lake among the highest-risk, which is 10 % of approximately 3,300 Himalayan lakes in terms of avalanche impacts, mainly due to its steep surrounding slopes and short ($< 600 \text{ m}$) glacier-to-shore distance (Steiner et al., 2024).

The socio-economic context of high-mountain Nepal amplifies the consequences of such multi-hazard chains. High-altitude regions of Nepal (such as the Manaslu area) are characterized by remote settlements with limited infrastructure and emergency services, as well as non-diversified livelihood options. These factors collectively amplify social vulnerability and constrain resilience. A recent nationwide Vulnerability and Risk Assessment (VRA) by the Government of Nepal (2023), with the second National Adaptation Plan, ranks high-altitude rural municipalities (including Chum Nubri) among the country's most climate risk-prone areas. Indicator-based studies, including a Multidimensional Livelihood Vulnerability Index for the Hindu Kush Himalaya (Gerlitz et al., 2016) and a modified Social Vulnerability Index for Nepal (Aksha et al., 2019), suggest that adaptive capacity factors (e.g., diversified livelihoods, strong social networks, and access to early-warning information) can mitigate some hazard exposure. Strengthening community-based disaster risk reduction,

improving access to information, and integrating scientific hazard forecasts with local knowledge have been repeatedly highlighted to build resilience in these regions (Hewitt & Mehta, 2012; Rasul et al., 2021). However, despite these recognized adaptive strategies, real-time avalanche warning systems and adequate studies linking hazard forecasts with local communities remain scarce in these high-altitude communities (Tuladhar et al., 2021).

Therefore, recognizing these challenges, we employ an interdisciplinary approach that combines field observations and semi-structured interviews with geo-morphological, climatic, and hydrological analysis to identify combinations of geomorphological features (e.g., slope angle, terrain roughness) and meteorological conditions that drive the region's frequent avalanches. We also examine how terrain and glacier characteristics influence avalanches in Birendra Lake, and evaluate the extent to which long-term temperature and precipitation trends have influenced avalanche frequency. In addition, we assess how local communities and local authorities (specifically the Samagaun Police Station) perceive, prepare for, and respond to these hazards. Finally, this study tests three hypotheses: First, the 30° - 45° slopes and the detached Manaslu Glacier terminus are the primary physical triggers for frequent avalanches. Second, regional warming and changes in the precipitation pattern have increased avalanche frequency. And third, limited early-warning capacity has led to a normalization of avalanche risk among downstream residents.

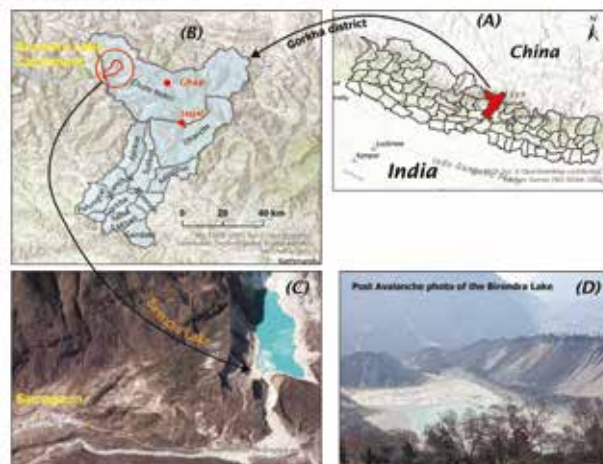
Data and methods

Study area

Birendra Pro-glacial Lake (Figure 1), known as Birendra Tal (Lake), was named by the locals of Samagaun in honor of the late King Birendra Shah after he visited the Manaslu region. Birendra Lake is very popular among trekkers on the Manaslu Circuit, as it lies along the route from Samagaun to Samdo (on the way to Manaslu Circuit). The glacial lake is dammed by an end moraine, situated just beneath Mount Manaslu (8,163 masl) in the Chum Nubri Rural Municipality of the Gorkha district in West-Central Nepal, at an altitude of 3,600 meters above sea level.

Figure 1

Location of Birendra Lake in Gorkha district



Note:

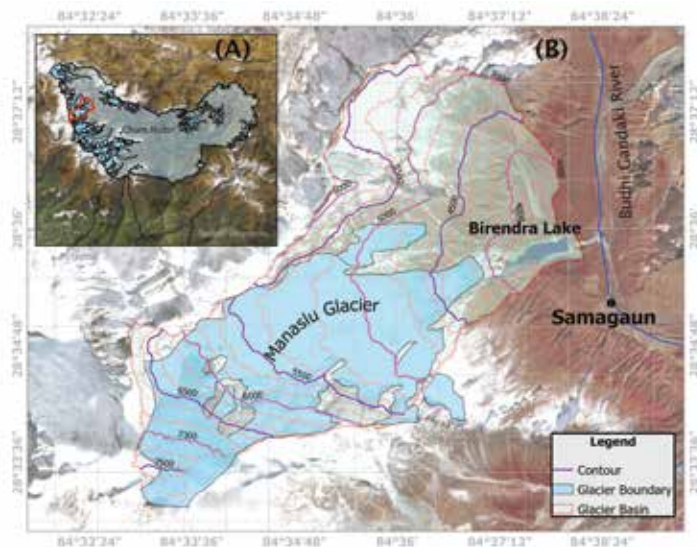
A. Nepal with district boundaries with the location of Gorkha district, B. Local municipalities of Gorkha district with Birendra Lake in Chum Nubri Rural Municipality with Ghap hydrological station 22 km downstream from Birendra Lake and Jagat hydrological station 25 km downstream from Ghap station, C. Google Earth image of Birendra Lake showing its outlet and Samagaun Village; and D. Post Avalanche image of Birendra Lake taken on 23 April 2024.

Birendra Lake is a headwater of the Budhi Gandaki River basin, located in central Nepal between longitudes 82°55' and 85°50' E and latitudes 29°15' and 28°05' N. According to Randolph Glacier Inventory version 7, there are 244 glaciers with a total area of 311.86 km² within the Chum Nubri Rural Municipality of the Gorkha district (Figure 2). The glaciers' size ranges from 0.02 km² to 32.81 km², whereas the size of the Manaslu Glacier is 15.28 km².

Birendra Lake is the moraine-dammed lake fed by the Manaslu Glacier. However, at the present moment, the glacier has since become entirely detached from the lake, exposing a steep slope and bedrock behind it, as illustrated in Figure 3A. The declassified KH-4A satellite image analyzed by Khadka et al. (2024) indicates that Birendra Lake had a size of ~0.25 km² at the terminus, indicating its formation began well before the year 1967. Since the Little Ice Age, the Manaslu Glacier has retreated over 1500 meters, and its surface elevation has decreased by more than 200 meters (Lee et al., 2021), significantly contributing to the formation and expansion of the lake. Notably, Khadka et al. (2024) documented a ~0.09 km² reduction in lake area between 1977 and 1988, possibly resulting from a glacier collapse or glacial lake outburst event. The lake's terminal moraine exhibits a distinctive V-shaped trench accompanied by a debris fan, suggesting past geomorphological activity likely tied to such events.

Figure 2

Manaslu Glacier Basin



Note:

A. Distribution of glaciers within Chum Nubri Rural Municipality, and B. Manaslu Glacier Basin

showing Manaslu Glacier and Birendra Lake with a contour interval of 200 m and 500 m. The background image is Sentinel-2, dated 26 November 2023.

Source: RGI version 7

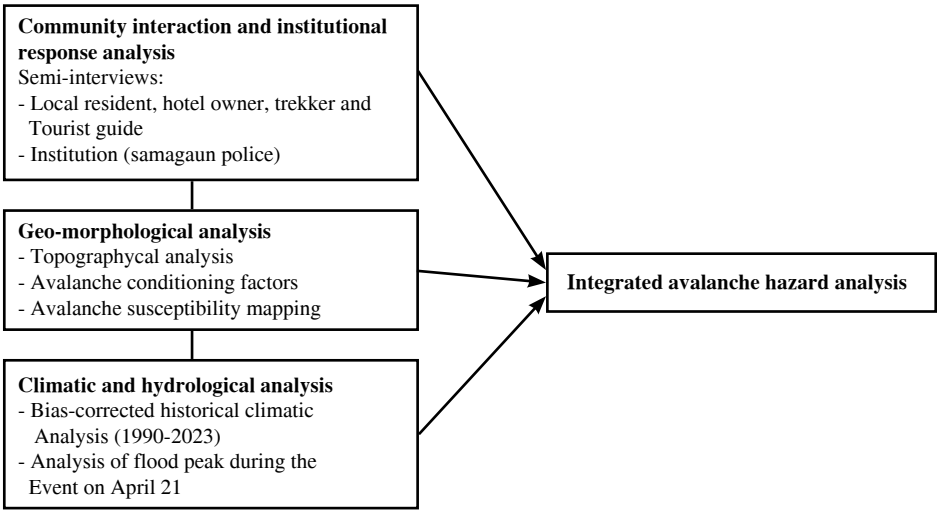
Methods

This study integrates an interdisciplinary methodology to investigate the recurring avalanche hazards in the Birendra Lake region, including the notable event of April 21. The approach integrates field-based observations, geo-morphological assessments, climatic and hydrological analysis, and community-based inquiry to understand the complex interactions between physical and social dynamics contributing to avalanche risk.

We developed a conceptual framework to guide this investigation and illustrate how these diverse components interact to inform an integrated avalanche hazard analysis (Table 1). The framework links three key domains: (i) community interaction and institutional response, (ii) geo-morphological analysis, and (iii) climatic and hydrological analysis. Each study domain contributes complementary insights into the drivers and impacts of avalanche hazards around Birendra Lake.

Table 1

Conceptual framework for integrated avalanche hazard analysis at the birendra lake region



The following sub-sections describe each framework component in detail, outlining the data sources, analytical methods, and field activities used in this study.

Community interaction and institutional response analysis

We conducted a transect walk and semi-structured key informant interviews during a field visit on April 23rd & 24th, 2024, to understand community perceptions and institutional responses to such hazards. This method targeted individuals with long-term experience and functional roles in the Manaslu region, including trekking guides, randomly encountered trekkers, hotel/lodge owners, and officers at the Samagaun Police Station. Each individual offered diverse yet complementary insights shaped by their direct exposure to climatic events and institutional response mechanisms. The interviews aimed to explore personal experiences

with avalanche events, observed climate changes, and perceptions of risk and preparedness.

Geo-morphological analysis

To understand terrain-based avalanche susceptibility, a geo-morphological assessment was performed using high-resolution satellite imagery, Google Earth, and a digital elevation model (DEM) based on the slope categories to identify avalanche conditioning factors, highlighting that the Birendra lake surrounding and the Mansulu region are at a higher risk for the frequent avalanche due to steep slope, rugged terrain, and the proximity to the Manslu Glacier.

Climatic and hydrological analysis

Temperature and precipitation data were bias corrected for the climatic analysis using observed datasets from the Ghap meteorological station, located approximately 22 km downstream of Birendra Lake. Precipitation data from Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) were also bias-corrected using the multiplicative scaling method (Sperna Weiland et al., 2010), expressed as:

$$P_{corrected_MOD} = \left(\frac{P_{obs}}{P_{MOD}} \right) P_{MOD} \quad \text{-----(I)}$$

Where P represents the monthly precipitation (mm), and $\bar{P}$ denotes the monthly average precipitation. In this study, CHIRPS is referred to as the modeled dataset (MOD).

Similarly, temperature data from ERA5 Land developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) were bias-corrected using the Cumulative Distribution Function (CDF) matching method in equation (II) proposed by (Piani et al., 2010), expressed as:

$$T_{corrected_MOD} = F^{-1}_{obs}(F_{MOD}(T_{MOD})) \quad \text{-----(II)}$$

Where F_{MOD} and F_{obs} are the CDFs of the modeled and observed temperature distributions, respectively, and F^{-1} represents the inverse CDF. Here, T_{MOD} and $T_{corrected_MOD}$ denote the raw and bias-corrected temperature data, respectively.

Additionally, the hydrological analysis included the interpretation of the flood peak associated with the April 21 avalanche event, using the data recorded at the Water Level Radar Stations at Ghap and Jagat.

Integrated analysis approach

The outputs from the community-level assessments, geomorphological modeling, and climate-hydrological corrections were utilized to produce a comprehensive avalanche hazard profile for Birendra Lake. This integrated analysis informed the understanding of physical vulnerabilities, local adaptation capacities, and institutional gaps in hazard management.

Data sources

This study integrates multiple data sources to assess the avalanche hazard of the Birendra Lake region. Remote sensing data were primarily obtained from Google Earth and Sentinel-2 imagery (dated 26 November 2023) to observe changes in glacier morphology and lake development. For terrain analysis, an ALOS PALSAR Digital Elevation Model (DEM), a radiometric terrain corrected and with a 12.5-meter resolution, was acquired from the Alaska Satellite Facility dataset to generate a slope-based avalanche susceptibility map.

Climatic datasets were sourced from two major reanalysis products: ERA5-Land, which provides temperature data from 1990 to the present (Muñoz-Sabater et al., 2021). It is widely used in climate change studies to capture warming trends and regional variations (Amjad et al., 2020). Similarly, CHIRPS is a satellite-based precipitation dataset with a high spatial resolution of 0.05° grid, which offers precipitation data from 1981 to the present and the capability to detect changes in precipitation patterns over time. It can effectively capture precipitation variability, which can be used for bias correction (Du et al., 2023).

Hydrological data were obtained from automatic radar water level sensors installed by the Himalayan Cryosphere, Climate and Disaster Research Center (HiCCDRC), Kathmandu University. These included real-time water level records from Ghap and Jagat stations, which captured significant surges during the April 21, 2024, avalanche event. The dataset is illustrated in Table 2.

Table 2
Summary of the dataset

Data type	Source	Timeframe	Purpose/Use
Satellite imagery	Google Earth, Sentinel-2 (ESA)	2019, 2023	Morphological analysis and mapping
Digital Elevation Model (DEM)	ALOS PALSAR (12.5 m resolution)	2009	Slope analysis for avalanche susceptibility mapping
Temperature data	ERA5-Land (ECMWF)	1990–2023	Long-term temperature trend analysis
Precipitation data	CHIRPS (Climate Hazards Group)	1981–2023	Long-term precipitation pattern analysis
Ground station data	Ghap Station (Kathmandu University)	2024/01/01-2025/02/28	Bias correction for reanalysis datasets
Photographs	Field survey	2024/4/23	Geomorphic characterization
Hydrological data	Water Level Radar Stations at Ghap and Jagat (HiCCDRC, KU)	April 2024	Observe the water surge during the avalanche event
Qualitative data	Semi-structured interviews (locals, police, guides)	23 rd to 25 th April 2024 (field visit)	Understanding community perception and institutional response

Results and discussion

Field observation

During the aftermath visit to the Birendra Lake on the third day following the avalanche event, the lake's water level had visibly dropped with numerous ice chunks (mixed with debris) floating on the lake's surface (Figure 3). Some of these chunks, comparable in size to rocks (as shown in Figure 3D), were scattered around the lake above its water level. Despite the overtopping, the lake's outlet remained structurally intact, though the outlet size had forcefully increased after the event. Additionally, continuous debris flow was observed entering the lake from the left side of the valley, adjacent to Birendra Lake and the Manaslu

Glacier, suggesting an ongoing sediment influx. Notably, how the incident was circulated raised questions about the lack of a prompt scientific investigation. Without clear communication or immediate research, the cause of the April 21 avalanche event remained ambiguous, leading to varied interpretations among local residents, tourist guides, and the media. While some attributed the event to rockfalls, others pointed to glacier collapse or snow avalanches. Figure 4 and 5 show the surroundings of Birendra Lake and avalanche source.

Figure 3

The condition of Birendra Lake after the avalanche event



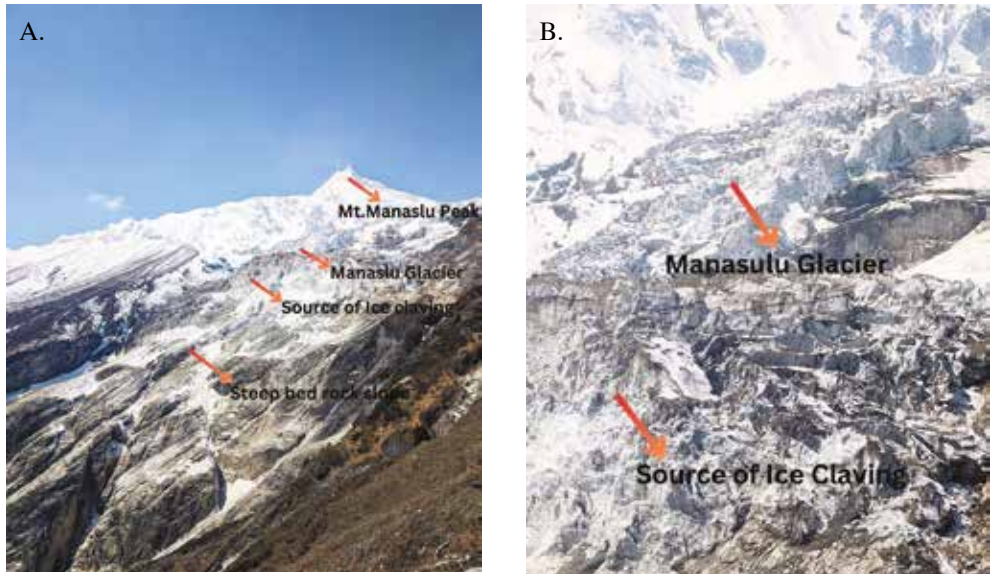
Note:

A. B. & D. show ice debris deposition on the lake's surface three days after an avalanche event, and C. shows a chunk of the mass of ice away from the lake.

@Manavi Chaulagain on 24 April 2024.

Figure 4

Manaslu glacier and Ice avalanche source



Note:

A. Mt. Manaslu peak and glacier, and B. Manaslu glacier and ice avalanche source, photo taken from the Manaslu base camp.

@Manavi Chaulagain on 24 April 2024.

Figure 5

Debris deposition and farsight view of Birendra Lake



Note:

A. Farsight view of Birendra Lake, and B. Debris deposition flowing from the adjacent valley to the left side of Birendra Lake.

@Manavi Chaulagain on 24 April 2024.

Observations and insights from Samagaun people on the event

Before reaching Samagaun, where Birendra Lake is situated, we were preoccupied with thoughts about the avalanche event: its potential impact, the local community's response, and the broader atmosphere in the aftermath of the avalanche. However, upon reaching Samagaun, we observed how normal everything seemed for the communities, as there were no visible concerns among the residents about the avalanche. For the people of Samagaun, avalanches are not unusual; they occur annually and are regarded as a regular part of their lives. The only recurring loss they face each year is the destruction of the wooden bridge that connects the trekking trails from Samagaun to Samdo. Every year, an avalanche sweeps away the bridge, and each time, the community rebuilds, which has become a regular scenario and practice for them. This attitude towards the event demonstrated a cycle of adaptation that reflects both resilience and normalization of hazard exposure for the people of Samagaun.

Insight from the local authority about the avalanche

In Samagaun, the only official governmental body present to ensure the security and well-being of the residents in case of any natural events like avalanches is the 'Samagaun Police Station'. The police station is a small unit with just seven officers, yet they have to cover the extensive area of 1,648.65 km² of Chum Numbri Gaupalika. Despite their limited numbers and scarce resources, these officers performed a wide range of duties crucial to the region's safety. They are involved in rescue operations as the first responders in emergencies. For instance, when tourists go missing during treks along the circuit, this small team mobilizes to find and bring them back to safety. They also play a key role in ensuring the general security of the local population and maintaining peace and order in the community. Additionally, they are tasked with making the community aware of various threats, from environmental hazards to potential social issues.

The police station in Samagaun does not have the authority to circulate news and information directly. They must first report every piece of information to the Arughat division responsible for disseminating news and early warning cautions. Though the protocol and chain of command are crucial for maintaining order and ensuring accurate communication, this hinders a swift response to the disaster. When we inquired about how they provide weather information to tourists who seek information and guidance about the conditions at the base camp or the high range, the response was disheartening. The officers admitted they had no answers due to the absence of weather forecast information and their lack of knowledge about weather conditions. The officer expressed hope that if the concerned authorities showed interest in making them aware of weather forecasts and climate change, it would greatly benefit their work.

Despite the event's significance, no stakeholders, agencies, NGOs, or INGOs showed concern for understanding the situation at Birendra Lake and the affected community until the third day, when media hype peaked about the event.

Insight while reaching Manaslu Base Camp

During the visit to Manaslu Base Camp, multiple snow avalanches were observed, reflecting the recurring nature of such events in the region, as reported by the locals. Within four hours, approximately seven to eight avalanches were heard, likely small in scale, as they did not appear to displace water from the nearby lake. Yet, they produced loud, resonating sounds across the area. Conversation with people in Samagaun emphasized that such avalanches are

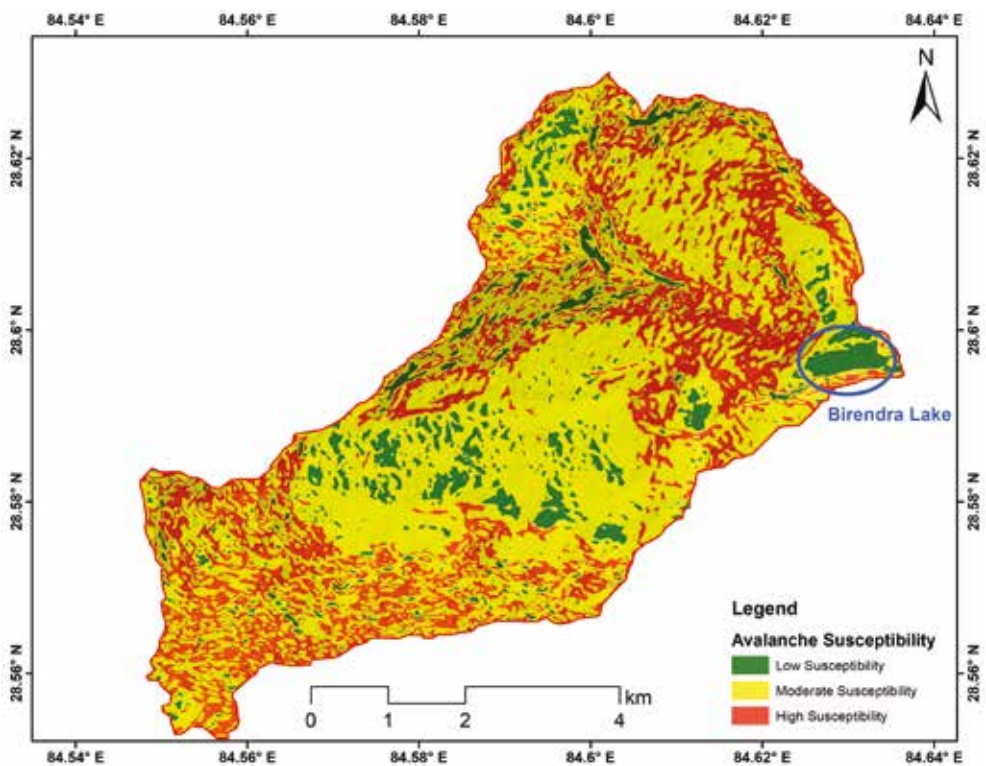
a frequent phenomenon in the area, underscoring the region's dynamic and unstable nature. These firsthand observations highlighted the urgency of understanding the frequency and impact of such events to develop effective risk mitigation strategies for both locals and trekkers.

Morphological analysis

The avalanche susceptibility of Birendra Lake and its surrounding terrain has been assessed by categorizing slope gradients, with large portions falling within moderate-to-high-risk zones (Figure 6). Studies suggest that slopes greater than 30° are particularly susceptible to avalanches (Corona & Stoffel, 2017). This key feature is also evident in our study of slope-based susceptibility mapping of the region.

Figure 6

Avalanche-susceptible zone map based on the slope category around Mt. Manaslu and Birendra Lake



The developed avalanche susceptibility map of the Birendra Lake region classifies the terrain into three distinct zones: high (30 - 45 degrees), moderate (10-30 degrees and 45-60 degrees), and low susceptibility (<10 degrees and > 60 degrees).

The map divides the terrain into three distinct zones based on slope angles:

- **High susceptibility (30–45°):** These steep, unstable slopes, highlighted in red, are most prone to avalanches, especially near glacier fronts or snowfields where snow can accumulate. Birendra Lake lies within this high-risk area, surrounded by steep terrain that makes it especially vulnerable to frequent avalanches.

- **Moderate susceptibility (10–30° and 45–60°):** Represented in yellow, these zones are characterized by slightly less steep slopes or more stable terrain. While the risk is lower than in high-susceptibility zones, avalanches can still occur under extreme weather conditions, such as heavy snowfall or seismic activity.
- **Low susceptibility (<10° and >60°):** Marked in green, these zones have gentler slopes or very steep areas where snow accumulation is minimal, resulting in a relatively low avalanche risk.

Further analysis by Maharjan et al. (2024) also highlights the Manaslu glacier's average slope of around 30 degrees and its snouts, which are separated from the lake by about 600 meters with a slope of approximately 39 degrees, emphasizing the lake's susceptibility to frequent avalanches. Furthermore, the proximity of the Budhi Gandaki River raises concerns about potential downstream impacts from avalanche-induced water surges, as evidenced during the April 21, 2024, event. These findings underscore the importance of implementing risk management strategies, including monitoring high-risk zones and establishing early warning systems to mitigate potential hazards.

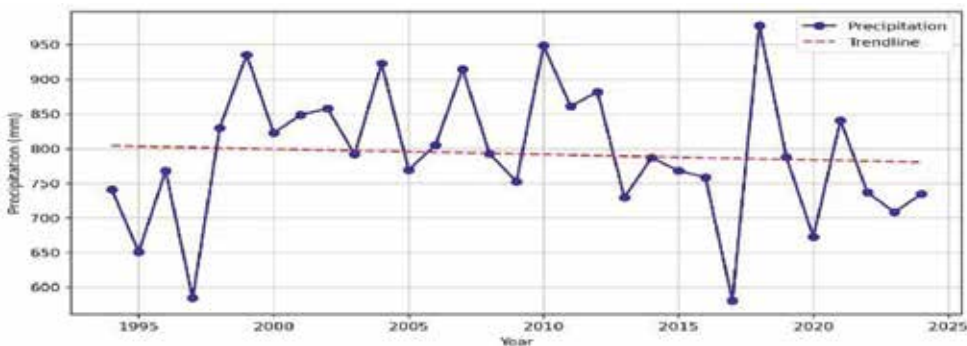
Climatic analysis

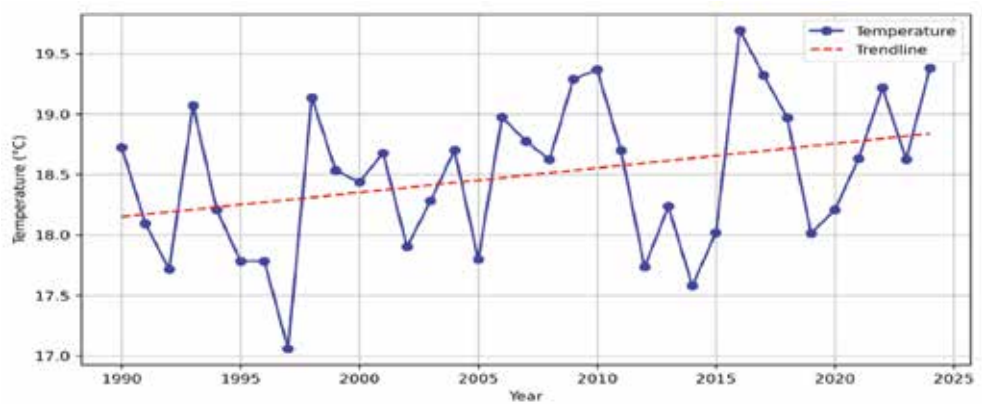
Following the bias corrections of ERA5-Land and CHIRPS, the results indicate a consistent warming trend in mean temperature over the years (Figure 7A). In contrast, the precipitation trend (Figure 7B) displays a slight decreasing pattern; however, this trend is statistically insignificant, suggesting no definitive change in total precipitation amounts over time.

While total precipitation does not show a significant trend, the implications of climate change may be more significant. A key concern is the potential shift in the phase and timing of precipitation, with increased temperatures possibly causing a higher proportion of precipitation to fall as rain rather than snow. This shift can have critical impacts on the hydrological regime, including earlier snowmelt, reduced snowpack stability, and an increased frequency of rain-on-snow events, all of which can enhance avalanche risk and contribute to glacier mass imbalance.

Figure 7

Temperature and precipitation trend of Chum-Numbri Municipality





Note:

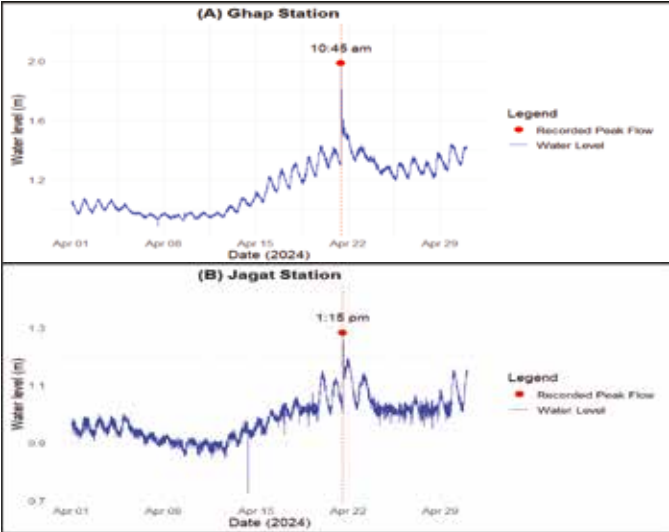
A. Mean annual temperature trend of Chum-Numbri Municipality, and B. Total annual precipitation trend of Chum-Numbri Municipality.

Peak water level recorded by the water level radar stations during the incident

According to the water level data available from the two automatic water level radar stations in Budhigandaki River at Ghap (2,089 m), 22 km downstream from the lake, the water level increased from 1.29 m at 10:25 am to 1.98 m at 10:45 am (a total of 69 cm increase). Similarly, the water level recorded at Jagat (1,350 m), 25 km downstream from the Ghap station, shows that the water level increased from 1.02 m at 12:45 pm to 1.28 m at 1:15 pm (a total of 26 cm increase) on April 21.

Figure 8

Peak water level at Ghap and at Jagat



Note:

A. Peak water level recorded by the water level radar station at Ghap, 21 April 2024. and B. Peak water level recorded by the water level radar station at Jagat, 21 April 2024.

Discussion

This study highlights the heightened vulnerability of Birendra Lake and the broader Manaslu region to avalanche-induced hazards, driven by a convergence of steep and rugged topography, proximity to the Manaslu Glacier, and dynamic climatic conditions. The April 21, 2024, avalanche incident further exemplifies how these factors converge to pose serious downstream risks. Although the lake is relatively small in surface area, 0.26 km², it holds substantial hazard potential, as evidenced by displacing a significant volume of ice and debris that generated the surge waves, raising water levels by 69 cm and 26 cm at Ghap and Jagat stations, respectively.

Using the volume estimation equation proposed by Zhang et al. (2023) ($V = 42.95 \times A^{1.408}$), a hypothetical breach of Birendra Lake could release approximately 6.44 million m³ of water. Though not extremely large, this volume would be sufficient to trigger significant flooding impacts downstream.

A comparative analysis with other Himalayan glacial lakes, such as Imja Lake in the Everest region, reveals both similarities and disparities. While both are moraine-dammed and located near retreating glaciers, Imja has undergone significant mitigation efforts, including a 3.4 m drawdown project in 2016 to reduce GLOF risk (ICIMOD, 2017; Somos-Valenzuela et al., 2016). In contrast, Birendra Lake, despite being categorized as high-risk due to its steep surrounding slopes and <600 m glacier–lake distance (Rounce et al., 2017; Zhang et al., 2023; Steiner et al., 2024) it has not been the focus of systematic monitoring or mitigation efforts yet. This discrepancy reflects a gap in hazard prioritization and preparedness strategies.

Birendra Lake presents a distinct multi-hazard cascade, where an avalanche may trigger lake overtopping, potentially leading to flash floods downstream. This layered hazard profile echoes past events like the 1985 Dig Tsho disaster in Nepal and the Laguna 513 flood in Peru, both triggered by icefalls into glacial lakes, resulting in catastrophic GLOFs (Byers, 1986; Carey et al., 2012). These events and the April 2024 avalanche demonstrate that even smaller-volume lakes can unleash destructive forces when subjected to sudden slope failure. The Table 3 offers a comparative overview of significant avalanche events in the Himalaya, showcasing diverse triggers, estimated volumes, and varying downstream effects.

Table 3

A comparative overview of avalanche events in the Himalayas

Date	Location	Trigger type	Estimated volume	Impacts	Reference
21 April 2024	Birendra Lake, Gorkha	Ice and debris avalanche	~0.2 million m³	Lake overtopping, downstream flooding, the bridge, and the hydropower plant affected	Field observation
12 February 2021	Mount Dhaulagiri, Myagdi	Winter storm avalanche	Unspecified	7 fatalities, including climbers, major avalanche from snowstorm	BBC News (2021); Himalayan Times

13 October 2015	Langtang Valley, Rasuwa	Earthquake-triggered snow avalanche	Unspecified	Village buried, 243 fatalities, massive destruction	Kargel et al. (2016); ICIMOD report (2015)
20 April 2014	Everest Base Camp, Khumbu	Icefall avalanche	50,000 m ³	16 fatalities at Everest Base Camp, triggered by a serac fall	Fujita et al. (2017); Media sources
5 November 1995	Manang District	Heavy snowfall-induced	Unspecified	Multiple injuries and livestock loss, houses damaged	Thakuri et al. (2020)
4 August 1985	Dig Tsho, Everest Region	Ice avalanche into the glacial lake	~10 million m ³ (with GLOF)	A glacial lake outburst flood destroyed the hydropower plant and bridges	Byers (1986); ICIMOD archive

Climatic trends across the Hindu Kush Himalaya (HKH) add a further dimension of risk. Regional warming rates of $+0.28^{\circ}\text{C}$ per decade since 1951 (ICIMOD, n.d.) are outpacing the global average, with temperature increases in HKH reaching $1.8\pm0.4^{\circ}\text{C}$ for every 1.5°C of global warming. Although long-term precipitation trends remain statistically insignificant, our bias-corrected climatic analysis confirms a steady warming trajectory (Figure 7). Rising temperatures are shifting the phase and timing of precipitation, reducing snowfall and increasing erratic rainfall, impacting avalanche formation and snowpack stability. The decreased persistence of snow, increased rain-on-snow events, and earlier melt cycles collectively exacerbate slope instability and glacial retreat. For instance, in Jumla, residents have observed a noticeable reduction in snowfall over the past several years. What once accumulated as deep snow lasting for weeks now melts within a day, indicating a shift toward rain-dominated winter precipitation (Practical Action Nepal, 2010). Such localized changes support the notion that precipitation phase transitions, even without significant changes in total volume, are critical to understanding evolving avalanche and hydrological risks in high-mountain environments.

Despite the clear signs of a changing hazard landscape, the April 2024 event, one of the largest recorded in the region according to the resident, highlights several gaps in the scientific and social framework. The lack of continuous monitoring at Birendra Lake left local communities and authorities ill-equipped to interpret or respond to the incident in real time. Conflicting reports from local sources and media about labeling the event alternately as an avalanche or GLOF illustrate a significant gap in scientific communication. This ambiguity, compounded by the absence of real-time hazard data, created confusion among residents and trekkers, disrupting livelihoods that depend heavily on tourism.

Community resilience, while admirable, reveals deeper issues. The routine reconstruction of wooden bridges after flood damage indicates strong adaptive responses, yet also reflects a lack of understanding about the increasing frequency and complexity of such hazards. The assumption that "nature will heal itself" may hinder proactive adaptation. Furthermore, information bottlenecks within institutional channels, such as delays caused by hierarchical communication protocols at the Samagaun Police Station, impede timely disaster response and public alerting.

This study argues for an integrated, forward-looking risk framework incorporating avalanche dynamics into the broader glacial lake and climate hazards context. Strengthening early warning systems, expanding high-elevation monitoring infrastructure, and fostering media literacy in hazard communication are crucial. Moreover, prioritizing Birendra Lake for active study and intervention is not just justified; it is urgent, given the lake's demonstrated potential for initiating complex hazard cascades.

Conclusion

This study reveals the acute vulnerability of Birendra Lake and its surrounding terrain to avalanche-induced hazard cascades, underscored by the 21 April 2024 event. Through a multi-method approach integrating remote sensing, climatic analysis, field observations, and community interviews, we identified the critical interplay between geomorphic settings, changing climatic conditions, and limited institutional preparedness. The findings demonstrate that despite its small size, Birendra Lake can generate significant downstream impacts due to its steep adjacent slopes, proximity to the retreating Manaslu Glacier, and debris inflow factors that heighten its hazard profile within a changing Himalayan cryosphere.

Our assessment shows that the event exemplifies a multi-hazard cascade, avalanche leading to lake overtopping and downstream flooding, aggravated by insufficient early warning mechanisms and institutional constraints. Although Birendra Lake has been classified as high risk in previous regional hazard assessments, it has remained under-monitored, with limited scientific focus and no real-time data infrastructure. These gaps contributed to public confusion during the April 2024 event and disrupted the tourism-based economy due to misinformation and a delayed response.

The study emphasizes the urgent need for improved early warning systems, including the establishment of high-altitude weather and hydrological monitoring stations and real-time data communication channels. Furthermore, fostering community-based participation in hazard monitoring and preparedness can bridge scientific knowledge and local resilience. Strengthening institutions like the Samagaun Police Station with training, resources, and streamlined communication protocols is also essential to improve response efficacy during crisis events.

Finally, translating scientific evidence into actionable and accessible knowledge for policymakers, practitioners, and the media remains critical. Doing so will support proactive planning and foster climate-risk literacy at both institutional and grassroots levels. Addressing these gaps through integrated scientific, social, and institutional strategies is vital for building long-term resilience in high-risk, glacially influenced mountain regions like Manaslu.

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Students' perspectives on Indigenous Knowledge Systems (IKS) for promoting tourism in contemporary Nepal

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Abstract

Nepal, renowned for its rich historical, cultural, and ecological diversity, holds immense potential for the tourism industry. The nation's Indigenous Knowledge Systems (IKS), encompassing both tangible and intangible resources, form the bedrock of its tourism assets. Ancient engineering practices, rooted in the IKS, have contributed to the development of remarkable historical artifacts and structures that continue to attract visitors. However, despite the diverse range of tourism products available, the contemporary generations often overlook the significance of these inherited resources. This study examines the role of the IKS in modern tourism through a qualitative research approach, using thematic analysis integrated with narrative interpretation as its core methodology. Thematic analysis was facilitated by MAXQDA software, incorporating the students' perceptions and insights from secondary literature. The findings underscore the critical role of the IKS in preserving and promoting Nepal's cultural and historical identity. Students advocate for tourism strategies that prioritize community participation, respect for indigenous knowledge, and encourage sustainable practices. These strategies align with global trends emphasizing authenticity and local engagement as key factors for long-term success in tourism development. The study underscores the need for future research to develop actionable frameworks for integrating the IKS into tourism policy and management. By leveraging traditional wisdom and fostering its revitalization, Nepal can create unique tourism experiences while ensuring the conservation of its invaluable heritage for future generations.

Keywords: community participation, heritage, Indigenous Knowledge Systems (IKS), sustainability, tourism

Introduction

Tourism plays a vital role in local communities, particularly in knowledge management and the preservation of indigenous knowledge. Various stakeholders, including students, researchers and government contribute meaningfully to the tourism sector (Gautam & Thapa, 2023). Young travelers, especially students approaching maturity, represent a growing segment of the tourism industry, making their travel behavior and perspectives significant for understanding contemporary tourism dynamics (Olszewski-Strzyżowski, Pasek, & Lipowski, 2022). Researchers in the tourism sector are increasingly engaging with participatory approaches that provide fresh academic insights and contribute to the sustainable development of tourism.

Indigenous Knowledge Systems (IKS) represent a wealth of cultural wisdom accumulated through centuries of trial and error. Rooted in cultural traditions, the IKS shapes the identity of indigenous communities and influence their perspectives on nature, heritage, and

spirituality (Agrawal, 1995). Nepal, often regarded as a cultural paradise, exemplifies the intersection of tourism and indigenous knowledge. In Nepalese Hindu traditions, cows symbolize Goddess Laxmi, representing prosperity, while dogs are revered as the sacred vehicle of Bhairab (Gautam, 2023). However, perspectives on indigenous knowledge vary across different caste, ethnic, and religious groups, including Muslims and other communities (Agrawal, 1995). Despite its rich heritage, the IKS is often undervalued in modern discourse, yet it remains a crucial element of global cultural heritage (Shrestha et al., 2024). These knowledge systems are not only aesthetic representations of the past but also functional assets for contemporary tourism and cultural preservation.

Tourism and culture are interlinked at both macro and micro levels, where cultural expressions attract tourism, while tourism influences the preservation, promotion, or transformation of cultural practices. However, their core objectives often diverge—tourism focuses on economic growth and visitor experience, whereas culture emphasizes identity, continuity, and heritage preservation (Richards, 2018). This tension can lead to either mutual reinforcement or conflict, depending on how tourism engages with local cultural contexts. Culture, as an intangible tourism product, plays a crucial role in shaping economic and social attributes within tourist destinations (Nega et al., 2021). The documentation of cultural heritage, often based on ancient engineering principles, serves as a medium for preserving and promoting traditional knowledge. Historical archaeological sites stand as testaments to indigenous ingenuity, providing opportunities to integrate traditional architectural models into modern tourism development (Ahmad, 2006; Gautam & Thapa, 2023).

The KIS offers an inclusive framework for integrating native and historical perspectives into decision-making processes across multiple sectors, including tourism (Anderson, 2022). The IKS contributes to socio-cultural and economic development, as well as spiritual and social dimensions of tourism (Department of Science and Technology, n.d.). The rise of the IKS movement has reinforced the importance of traditional identity in tourism, leading to the increased recognition and utilization of indigenous knowledge in managing touristic resources (Butler, 2021). Moreover, traditional governance structures and Indigenous rights play a crucial role in shaping community-driven tourism models (Jackson, 2025).

Methodology

The methodological framework of this study began with a thematic analysis of relevant perspectives, which was subsequently followed by a review of the IKS. Ogegbo and Ramnarain (2024) reflect the IKS practices in knowledge system with the integration of pedagogical perspectives. The integration of these two processes resulted in a comprehensive synthesis that informed the foundation of the research. To supplement this groundwork, primary data collection was conducted to provide further depth and context. The study adopts a qualitative research design, leveraging literature reviews and students' perceptions to structure the data and insights presented. Specifically, study explores and analyzes the perspectives of various stakeholders engaged in indigenous tourism initiatives (Shrestha et al., 2024). The qualitative design served as the cornerstone of the research approach, enabling the authors to delve deeply into subjective experiences and interpretations. Primary data were collected from twenty-two recent graduates of the Public Administration Campus at Tribhuvan University. These respondents participated in the study through a semi-structured guideline, which was distributed via email.

Inter alia, the data collection process was based on an ethical way because all respondents were informed that they had the right to not take part. A total of 28 guidelines were sent, and 22 were responded to, so bias was minimized as possible. For research, understanding bias is important for several reasons (Smith & Noble, 2025). The respondents were the students of the prime researcher, but by the date of data collection, they were past students (graduated), and all of them were personally very comfortable exchanging information and knowledge. Careful participation with respondents is a more ethical and flexible way to minimize bias. The data analysis process employed thematic analysis combined with narrative interpretation to extract nuanced meanings and insights. This analysis was conducted using MAXQDA software, which facilitated efficient organization and interpretation of the data.

Findings and analysis

This research aims to uncover hidden truths and novel knowledge, as emphasized by Kothari (2004), who underscores the importance of exploring uncharted domains in academic inquiry. Within the context of Nepal, this study seeks to provide new insights into the relationship between tourism and IKS.

While narrative analysis has been previously employed in tourism research, its application remains relatively limited, particularly in exploring the specific forms of narrative analysis outlined by tourism scholars (Mura & Sharif, 2016). Therefore, this article adopts an exploratory research design, characterized by a focus on uncovering new dimensions and patterns in tourism and IKS. By the conclusion of the study, the article's approach transitions to an exploratory-cum-descriptive framework, aiming to provide both innovative insights and a comprehensive understanding of the phenomena under investigation.

Demographic interpretation of participants

This study conducted In-Depth Interview (IDI) with 22 participants. The average age of participants was approximately 24.5 years, most of them were between 22-27 years old. The most frequently occurring age was 24 years. In terms of gender distribution, the male participants were (14) and female participants were (8), with males making up about 64% of the sample and females around 36%. Regarding religion, the majority of participants (86%) were identified as Hindu, while one participants of Buddhist, and another had not specified their religious affiliation.

Understanding of the IKS

Students in the study recognize IKS as a repository of traditional wisdom passed down through generations, deeply intertwined with environmental, spiritual, and cultural practices. One participant noted, "indigenous knowledge is like a living library, constantly evolving and adapting to nature and society" (Participant 3). Figure 1 represents the terminologies used by the participants while discussing on IKS. Scholars such as Battiste (2002) emphasize that IKS embodies holistic, contextual, and community-driven knowledge systems that differ from the compartmentalized nature of Western epistemologies.

Perspectives on tourism management

Tourism management is perceived as a multidisciplinary field encompassing strategic planning, sustainability, hospitality, and cultural preservation. One participant described it as "a balancing act between economic gain and cultural respect" (Participant 7). Hall and Page (2014) assert that successful tourism management requires integrating local cultural values with global tourism trends to ensure responsible and ethical development.

A strong theme emerging from the discussions was the necessity of integrating IKS into tourism management. As another participant emphasized, "tourism should not be about showcasing cultures as museum pieces but about creating meaningful engagements with living traditions" (Participant 10). This aligns with Smith's (2016) concept of cultural sustainability, which argues that tourism must serve as a means to empower indigenous communities rather than commodify their traditions.

Role of academic research in tourism

Students emphasized the role of academic research in bridging the gap between IKS and tourism. Research was metaphorically described as a "GPS that helps navigate cultural tourism while avoiding ethical pitfalls" (Participant 5). Scholars like Ryan and Aicken (2010) highlight the importance of ethnographic research in ensuring that tourism development does not exploit indigenous knowledge but rather fosters mutual benefits for communities and stakeholders.

However, concerns were raised about extractive research practices. Some students expressed scepticism about academic studies that treat indigenous communities as subjects rather than partners. This critique is echoed in Smith's (1999) *Decolonizing Methodologies*, which warns against the appropriation of indigenous knowledge without proper recognition and benefit-sharing.

Interpretation of tourism management course

While students generally appreciated the curriculum's focus on strategic planning and policy-making, some felt it remained too theoretical. A participant remarked, "we learn about sustainability in books, but we rarely engage with the indigenous communities who practice it" (Participant 12). Weaver (2011) suggests that tourism education should incorporate experiential learning, allowing students to interact with local knowledge holders. Traditional systems, despite their sustainability potential, are often undervalued in formal tourism education. According to Sharma (2020), integrating IKS into tourism courses could enhance students' understanding of sustainability by providing real-world applications of ecological and cultural knowledge.

Role of traditional systems in tourism

Nepal's diverse traditional systems: rituals, festivals, hospitality customs, and community networks are seen as key assets for tourism. The philosophy of 'Atithi Devo Bhava' (Guest is God) remains central to Nepalese hospitality. A student observed, "When tourists stay in village homestays, they don't just visit Nepal; they experience it" (Participant 14). Research by Reisinger (2009) suggests that authentic cultural experiences are among the most sought-after aspects of tourism, reinforcing the economic and social value of traditional practices.

Perception of the IKS in promoting tourism

Students strongly believe that IKS is crucial for differentiating Nepal's tourism industry from travel experiences. A participant shared, "our medicinal plants, festivals, and crafts offer something unique that modern tourism cannot replicate" (Participant 8). Berkes (2012) supports this claim, arguing that indigenous ecological knowledge can play a significant role in sustainable tourism by promoting conservation-oriented travel.

However, students also raised concerns about over-commercialization. One remarked, "when traditions become performances for tourists, they lose their meaning" (Participant 15). This aligns with Heilman & MacCannell's (1977) critique of staged authenticity, where cultural experiences are often adapted to meet tourist expectations, sometimes at the cost of their original significance.

The IKS in tourism development

Many participants argued that Nepal has long benefited from indigenous tourism, attracting scholars, researchers, and travelers interested in its cultural and spiritual heritage. A participant highlighted, "before global tourism trends, pilgrims, traders, and researchers came to Nepal to experience its knowledge systems" (Participant 6). Hall & Smith (2000) note that heritage tourism is deeply rooted in indigenous traditions, and its sustainable management requires collaboration between communities and policymakers. Participants also noted the role of government policies and the Nepalese diaspora in promoting the IKS-based tourism. Cultural tourism accounts for a significant portion of Nepal's tourism revenue, emphasizing the need for policies that support indigenous-led initiatives (Kandel, 2011).

Discussion

Nepal's cultural and ecological richness offers a compelling context to explore the integration of the IKS into tourism. The findings of this study underscore how it serves not merely as a cultural backdrop for tourism but as an active, living force that shapes the identity, sustainability, and resilience of the tourism sector in Nepal. This section critically evaluates the intersection of the IKS with tourism, addresses theoretical insights from contemporary literature, and reflects on emerging challenges such as commodification, sustainability, and epistemic justice.

Participants viewed the IKS as a "living library" (Participant 3), a term that resonates with scholars like Battiste (2002), who emphasizes that Indigenous knowledge is not static but fluid, adapting to socio-environmental contexts. Unlike compartmentalized Western epistemologies, the IKS in Nepal holistically integrates spiritual, ecological, medicinal, and ethical dimensions. This multidimensionality positions the IKS as an invaluable framework for sustainable tourism.

One of the most illustrative examples of IKS in Nepal is the "Guthi" system—a socio-religious institution that manages rituals, architecture, land, and communal responsibilities. While some participants viewed the Guthi as outdated, others emphasized its role in preserving cultural identity. As Berkes (2018) argues, Indigenous institutions often carry embedded sustainability practices, with the capacity for adaptation. The Guthi system, therefore, can be reinterpreted in modern tourism as a community-based model for managing cultural heritage and rituals in a participatory manner.

Nepal's demographic complexity—with over 142 caste and ethnic groups and 122 languages (National Statistics Office, 2023; Gautam, 2023)—creates a unique tourism proposition. Rather than homogenized or mass-market tourism, Nepal offers layered cultural experiences rooted in localized knowledge systems. From medicinal plant knowledge among the Tamang to intricate Tharu crafts or the agrarian calendars followed by the Newars, this cultural depth allows Nepal to offer what MacCannell (1976) calls “authentic experiences” in contrast to artificial “staged authenticity.” The differentiation of regional traditions—if framed ethically—can enhance the uniqueness of Nepal's tourism branding while resisting cultural flattening.

The integration of the IKS into tourism management was a recurrent theme among participants. As Participant 7 described, “tourism requires a balancing act between economic gain and cultural respect”. This insight aligns with Hall and Page's (2014) framework that successful tourism models must weave together local cultural systems and global market dynamics. The IKS can serve as a bridge between these poles, offering culturally grounded solutions to modern challenges, including environmental degradation, cultural loss, and community disempowerment.

Yet, a core tension emerges around the commodification of indigenous traditions. As tourism demand grows, rituals and festivals risk becoming performative rather than meaningful. This mirrors concerns raised by MacCannell's (1976) critique of “staged authenticity”, wherein cultural practices are modified to meet tourist expectations, thus eroding their original significance. For example, while the Bisket Jatra festival is a major tourist attraction, some local practitioners worry that its ritualistic meaning is being diluted in favor of spectacle. Ensuring that these events remain rooted in their cultural contexts requires both regulatory frameworks and community stewardship.

The study further illuminates how the IKS contributes to sustainability—not just culturally, but environmentally and economically. Traditional architectural practices such as the Newar system of earthquake-resistant design use local materials and reflect a profound understanding of environmental adaptation. These methods, if scaled through policy and tourism infrastructure, can serve as models of ecological resilience. Similarly, Nepal's ethnobotanical traditions—such as herbal treatments and sacred groves—can be integrated into wellness and eco-tourism, two fast-growing segments of the global travel market (Berkes, 2012).

Participants also discussed the role of academic research in navigating the ethical dimensions of cultural tourism. As Participant 5 aptly stated, “academic research is like a GPS—it helps us navigate but shouldn't replace local knowledge”. This echoes Tuhiwai Smith's (1999) critique in *Decolonizing Methodologies*, which warns against extractive research practices that treat indigenous communities as data sources rather than knowledge partners. In Nepal, many studies on tourism have disproportionately benefited researchers while sidelining community voices. To redress this imbalance, research institutions must adopt participatory approaches that include benefit-sharing mechanisms and co-authorship.

In this regard, experiential learning models can bridge the gap between academia and community knowledge. As Weaver (2011) notes, embedding students in field-based ethnographic learning helps them understand the lived realities of the IKS rather than approaching it abstractly. Such models can also facilitate community-led tourism innovations that draw upon deep-rooted cultural knowledge, rather than externally imposed solutions. Integrating the IKS into tourism curricula, as suggested by Sharma (2020), can thus produce

more grounded tourism professionals capable of implementing culturally sensitive and sustainable policies.

Nepalese hospitality itself is a reflection of the IKS. The principle of “Atithi Devo Bhava” (Guest is God) underlies the experience of many homestays and village visits. Tourists are not merely customers but are treated as temporary family members, leading to immersive cultural exchanges. Reisinger (2009) highlights that such authentic, person-to-person experiences are becoming increasingly valuable in the tourism economy—not only enhancing visitor satisfaction but also ensuring that economic gains are retained locally.

Heritage tourism continues to be a significant pillar of Nepal’s tourism economy, built on centuries of pilgrimage, trade, and cross-cultural exchange. From the spiritual routes of Pashupatinath and Muktinath to the centuries-old Tharu settlements and Newar urban centers, heritage tourism is inseparable from the IKS. As Hall and Smith (2000) note, the historical foundation of tourism in many parts of the Global South rests not on leisure but on knowledge-seeking and spiritual quests. This alternative genealogy of tourism should be recognized and leveraged to distinguish Nepal’s tourism identity globally.

Despite these strengths, the commercialization of indigenous culture remains fraught. The study reveals several threats, including over-tourism in sacred sites, erosion of traditional practices due to urban migration, and the spread of consumerist aesthetics that marginalize local art forms. Policymaking must confront these issues through both protective regulation and supportive measures for indigenous communities. Government tourism boards and the Nepalese diaspora play a crucial role in international promotion, but their narratives must be rooted in community realities rather than idealized projections.

Finally, the path forward for IKS-based tourism lies in indigenous leadership. Cultural sovereignty entails allowing local communities to determine how their traditions are shared, represented, and monetized. Whether through cooperatives, community trusts, or participatory councils, mechanisms must ensure that benefits from tourism are not only equitable but also reinforce cultural pride and transmission.

Conclusion

This study underscores the pivotal role of the IKS in shaping sustainable tourism practices in Nepal. Participants recognize the immense value of integrating the IKS into tourism management, policy-making, and academic research, highlighting its potential to promote ethical tourism and support the preservation of indigenous identities. The historical artifacts and practices derived from IKS embody not only cultural heritage but also innovative approaches to resource management, passed down through generations. However, the study also draws attention to the risks of over-commercialization and extractive research, which could compromise the authenticity and sustainability of these systems. Participants emphasize the necessity of strategies that prioritize community engagement, respect indigenous knowledge, and foster meaningful cultural exchanges. These priorities resonate with global trends in sustainable tourism, where local participation and authentic experiences are pivotal to long-term success.

The findings highlight the need for future research to explore actionable strategies for revitalizing the IKS within Nepal's tourism industry. By leveraging the rich repository of indigenous knowledge, both tangible and intangible cultural assets can be transformed into

unique tourism products that promote economic and social well-being. Moreover, the integration of the IKS into hospitality studies and tourism management has the potential to generate new knowledge and insights while preserving invaluable historical legacies. Study highlight the need for a balanced approach to tourism development: one that safeguards indigenous heritage, ensures inclusivity, and promotes sustainable practices for future generations. Through collaborative efforts, Nepal can harness the power of the IKS to enrich its tourism landscape while preserving its cultural and historical essence.

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Glacial Lake Outburst Floods (GLOFs) in the Nepal Himalayas: Recent events, urgent response, and global actions for cryospheric science

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Abstract

The Nepal Himalayas are experiencing an unprecedented rise in cryosphere-induced hazards, especially Glacial Lake Outburst Floods (GLOFs), as a result of rapid glacial retreat driven by anthropogenic climate change. Between 2024 and 2025, three major GLOF events, the Birendra Lake flood (April 2024), the Thame GLOF (August 2024), and the Limi Valley GLOF (May 2025) demonstrated the escalating frequency and intensity of such disasters. These events pose serious threats not only to vulnerable mountain communities and local biodiversity but also to globally significant mountain ecosystems, including the Sagarmatha National Park, a UNESCO World Heritage Site. This paper provides a comprehensive analysis of these recent events, identifies critical gaps in monitoring, preparedness, and response, and highlights the urgent need for improved integration of cryospheric science with local adaptation and international cooperation. By linking Nepal's experience with global frameworks like the International Year of Glacier Preservation (YIGP-2025) and the UN Decade of Action for Cryospheric Sciences (2025–2034), this study contributes new insights into the pathways for achieving equitable, science-driven, and community-based climate resilience.

Keywords: climate change, cryosphere, disaster risk reduction, GLOFs, glacier preservation

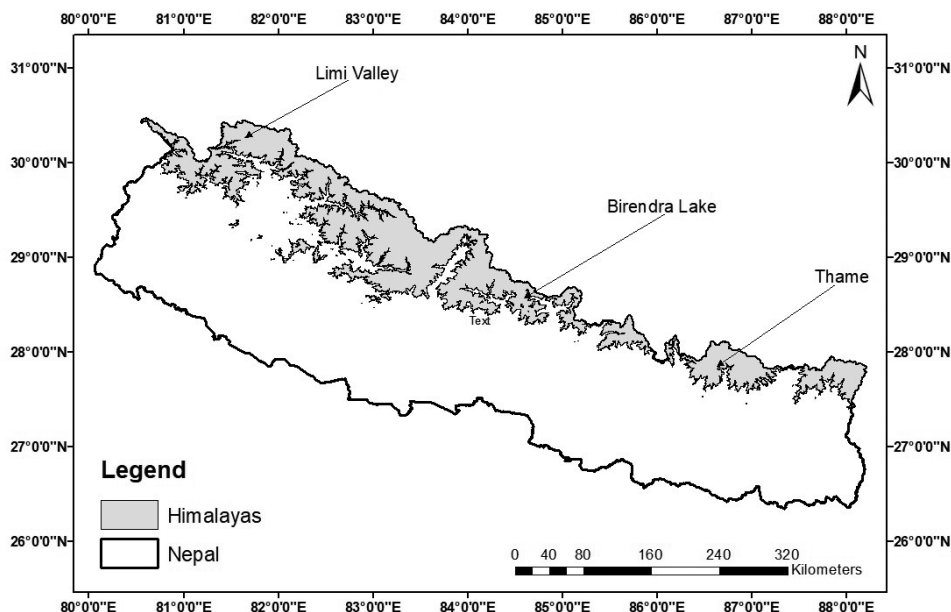
Introduction

The Himalayas, often referred to as the “Third Pole” due to their massive ice reserves, are a vital component of the global hydrological and climate systems. These high-altitude regions store freshwater that sustains the lives of nearly two billion people downstream (Chandrashekhar, 2020; UN-Water & UNESCO, 2025). However, warming rates in the Himalayas have outpaced global averages, resulting in glacial retreat, permafrost degradation, and the rapid expansion of glacial lakes (ICIMOD & UNDP, 2020).

The increasing risk of GLOFs, a sudden discharge of water from glacial lakes, has emerged as a critical concern for disaster risk reduction (DRR) and climate adaptation. Nepal, with over 3,000 glacial lakes (ICIMOD & UNDP, 2020), is particularly vulnerable. This paper examines three recent high-impact events and connects them to broader national and international responses in science, policy, and community-based action. Figure 1 presents a map of Nepal, highlighting the Himalayan region and the specific areas where the three significant cryosphere-induced events occurred.

Figure 1

Map of Nepal showing the Himalayan region and the locations of three recent high-impact GLOF events



Recent cryosphere-induced events in Nepal

Birendra lake flood (April 2024)

Birendra Lake, located in the Manaslu region of Gorkha District, is a moraine-dammed lake fed by the Manaslu Glacier. On 21 April 2024, an avalanche event triggered a partial lake outburst. Within 20 minutes, the Budhi Gandaki River surged by 69 cm at the Ghap hydrological station (Chaulagain et al., 2024, Khadka et al., 2025, Maharjan et al., 2024). Although there were no fatalities, the flood disrupted livelihoods and emphasized the vulnerability of even relatively small glacial lakes.

This event underscored a critical gap in the early warning systems (EWS) for avalanche-induced floods, revealing the urgent need for improved cryospheric hazard modeling and real-time monitoring in high-risk zones.

Thame GLOF (August 2024)

On 16 August 2024, a GLOF originating from the Thame glacial lake caused extensive damage in the upper Khumbu region, within Sagarmatha National Park. Over 200 households were affected, and several trekking routes and biodiversity corridors were severely damaged (Pradhananga, 2024). As the area is part of a UNESCO World Heritage Site, the event raised global concern regarding the impacts of climate change on heritage and conservation areas.

Subsequently, a rapid response project titled Thame GLOF 2024: A Rapid Response for Biodiversity Conservation of the Sagarmatha National Park was proposed to assess ecological damages and implement mitigation measures (Pradhananga, 2024).

Limi valley GLOF (May 2025)

On 15 May 2025, a catastrophic GLOF struck the Limi Valley of Humla district, one of the most remote regions in northwestern Nepal. The flood displaced dozens of households and caused severe damage to the Tilkhola micro-hydropower project, irrigation canals, residence structures, and even the local monastery (Shahi, 2025). Compounding the crisis, damaged roads and landslides cut off access to the area, delaying the arrival of relief materials by over a week. This event occurred shortly before the Sagarmatha Sambaad, an international dialogue held from 16 to 18 May 2025 in Kathmandu, which brought heightened global attention to the fragility of Himalayan communities (Sagarmatha Sambaad, 2025).

A global fundraising initiative (GoFundMe, 2025) quickly mobilized resources, but the event highlighted systemic issues in regional emergency preparedness and the need for resilient infrastructure in isolated mountain areas. This event underscores the cascading impacts of cryospheric change beyond the snow and ice itself, undermining essential services and forcing communities into unsafe conditions. It emphasizes the urgent need for integrated cryosphere monitoring and early-warning systems in remote Himalayan valleys.

Advances in monitoring and science

The growing urgency of recent GLOFs has sparked a coordinated, multi-stakeholder response involving universities, government bodies, NGOs, and international organizations. Key initiatives include:

- High-resolution hazard mapping using satellite imagery and UAV-based remote sensing,
- Participatory risk assessments are conducted at the community level,
- Enhancement of Early Warning Systems (EWS), and
- Promotion of nature-based solutions, such as afforestation and bioengineering.

These efforts are closely aligned with Nepal's National Adaptation Plan (NAP) and its DRR priorities under the Sendai Framework for Disaster Risk Reduction.

Evidence from Jumla in western Nepal, as featured in the publication "Voices of People" (Gurung et al., 2010), illustrates the stark transformations underway. Once characterized by consistent winter snow cover, the region has witnessed a steady decline in snowfall in recent years, posing serious threats to water availability, agriculture, and rural livelihoods.

Policy engagement and community participation

A key driver of this cross-sectoral effort has been the UNESCO Chair in Mountain Water Sustainability (University of Calgary, 2025), working in partnership with Tribhuvan University, Kathmandu University, ICIMOD, and the Department of Hydrology and Meteorology (DHM). Their collaborative initiatives focus on bridging the science-policy interface while empowering communities to play active roles in adaptation planning.

On 21 March 2025, Nepal marked the first World Day of Glaciers during the National Glacier, Water, and Weather Week (NNGWW-2025). The event featured the launch of the UN World Water Development Report 2025, which underscored the vital role of glaciers as the planet's "water towers" (UN-Water & UNESCO, 2025). Discussions emphasized

inclusive climate action, particularly women's leadership in adaptation, with strong representation from grassroots organizations such as The Small Earth Nepal (2025a).

Looking ahead, upcoming forums like the International Conference on Glacier Preservation (Dushanbe ICGP, 29–31 May 2025) continue to foster international collaboration. One of the authors will present Nepal's experience and lessons learned from the GLOF events, advocating for greater investments in climate-resilient infrastructure in the Hindu Kush Himalaya region

Finally, the People's Forum on Sagarmatha Sambaad jointly convened by several organizations including The Small Earth Nepal (2025b), offered a critical platform for integrating community perspectives into national climate policy discourse. The forum played a key role in shaping Nepal's contributions to global climate frameworks, reinforcing the importance of locally grounded adaptation strategies.

Global significance: IYGP-2025 and the UN decade of action for cryospheric sciences (2025–2034)

In December 2023, the UN General Assembly adopted Resolution, declaring 2025 the International Year of Glacier Preservation (IYGP) (United Nations, 2023). This initiative recognizes the global implications of glacial melt, particularly in the Himalayas, Andes, and polar regions.

Additionally, the launch of the UN Decade of Action for Cryospheric Sciences (2025–2034) calls for long-term investment in glacier monitoring, improved climate models, and stronger linkages between high mountain science and water governance. As global average temperatures approach the 1.5°C threshold, rapid glacial loss will become irreversible in many regions (Yasunari et al., 2010; Gul et al., 2021).

Integrating local initiatives, like the Thame and Limi GLOF responses, into these global frameworks is essential for delivering equitable and actionable climate resilience.

Conclusion

The series of GLOF events in Nepal between 2024 and 2025 underscores the mounting risks posed by accelerating cryospheric change in the Himalayas. With glacial lakes growing rapidly, cryosphere-related hazards are becoming more frequent, devastating local communities, ecosystems, and critical infrastructure. The recent events clearly demonstrate that cryospheric risks are no longer isolated incidents but systemic threats requiring integrated, multi-level responses.

Moving forward, Nepal's experience highlights the need to:

- Scale up real-time monitoring of glaciers and glacial lakes using satellite and drone-based technologies,
- Institutionalize community-based disaster preparedness and local ownership of adaptation strategies,
- Strengthen transboundary and regional cooperation across the Hindu Kush Himalaya,
- Integrate cryospheric science in both national climate strategies and global climate negotiations, and

- Accelerate international collaboration through initiatives such as the IYGP2025 and the UN Decade of Action for Cryospheric Sciences (2025–2034).

As a frontline country in the global cryospheric crisis, Nepal has a critical role to play in advancing scientific knowledge, advocating for vulnerable mountain populations, and contributing to global action for glacier preservation. Protecting the resilience of mountain communities today is essential for safeguarding freshwater resources and human well-being for generations to come.

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Expansion of Lirung Glacial Lake in the Langtang Basin, Nepal: Implications for mountain water sustainability and GLOF risks

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Abstract

Glaciers are natural reservoirs of freshwater that cater to the millions of people in a mountainous country like Nepal. However, these freshwater sources are retreating at an alarming rate, altering the downstream flow. Furthermore, this has led to an increase in glacier lake areas and their number, which may eventually be at risk of Glacial Lake Outburst Floods (GLOFs). This study focuses on the expansion of Lirung Glacial Lake in the Langtang Basin from 2010 to 2024, utilizing multi-temporal satellite imagery from Landsat and Sentinel. The Normalized Difference Water Index (NDWI) was applied to delineate lake boundaries, which were then analyzed in conjunction with climate data from the basin. The result shows that over 14 years, the lake's area has increased at an approximate rate of 0.0035 km² per year from 1.55 km² in 2010 to 6.36 km² in 2024, which is an increase of 60.8%, indicating significant glacier retreat. The mean annual temperature in the basin is increasing, and precipitation is slightly declining, which are conditions favourable for accelerated glacier mass loss. These findings underscore the heightened risk of GLOFs, with potential impacts on downstream communities and critical infrastructure, including Nepal's only glacial lake-fed micro-hydropower plant. The study highlights the urgent need for continuous monitoring, community-based early warning systems, and adaptive water resource management to safeguard mountain communities and their livelihoods in the face of climate change.

Keywords: climate change, glacial lake expansion, glacier retreat, GLOFs' Lirung glacial lake

Introduction

Glaciers are of considerable interest due to their high sensitivity to climate change (Zheng et al., 2022). The IPCC (2023) report states that glaciers will continue to lose mass for several decades even if global temperatures stabilize. In context of Nepal Himalayas, it has been warming at a rate of 0.02 °C - 0.16 °C per year in recent decades (Khadka et al., 2023), resulting in shifts in snowfall patterns, greater ice melt, and increasing of glacial lakes (King et al., 2019; Nie et al., 2013). Rapid climatic changes have altered the accumulation and melting patterns of snowfields and glaciers, increasing the size of glacier lakes and floods associated with them. Their retreat impacts water resources, influencing their basin hydrological regime due to their capacity to store water on seasonal to decadal time scales (Jansson et al., 2003).

Due to the rapid melting of glaciers, the number and area of glacial lakes have grown rapidly. Since 1990, global glacial lake area has increased by over 50% (Shugar et al., 2020).

According to Kumar et al. (2025), the number of glacial lakes in the Hindukush Karakoram region increased by 9.31% and their area expanded by 10.09% from 1990 to 2010. Furthermore, 110 GLOF events have been recorded in the Third Pole region since 1900, causing around 7,000 fatalities (Taylor et al., 2023). A recent report by Bajracharya et al. (2020) highlights that there are 21 potentially dangerous glacial lakes in Nepal, and this number is expected to grow further with unprecedented changes in the climate. For instance, a recent GLOF from Thyanbo glacier lake in Thame village of the Khumbu region lost properties, infrastructure, and biodiversity (ICIMOD, 2024). The outburst of Lhonak Lake in Sikkim in October 2023 killed over 150 people and destroyed infrastructure downstream (Pokhrel, 2024). Also in 1985 GLOF from Dig Tsho in the Everest region destroyed the Namche hydropower plant and caused USD 2 - 3 million in damage (Shah & Ishtiaque, 2025). These events underscore the urgent need to monitor expanding lakes and protect vulnerable communities.

The Langtang Basin in Nepal, where nearly half of the area is covered by glaciers, features the country's only glacial lake hydropower project. The proglacial lake at the terminus of the Lirung Glacier holds significance as it is Nepal's first glacial lake hydropower project, generating 100 kW of hydropower energy consumed by two villages, Kyanjing and Langtang, which comprise around 120-175 households (Dixit, 2021). The rapid expansion of Lirung Lake could increase the risk of a GLOF that would endanger not only downstream communities and tourism but also the hydropower infrastructure itself. In this context, our study focuses on (a) quantifying Lirung Lakes expansion from 2010 to 2024, (b) relating observed changes to climatic trends, and c) discussing implications for hydrology and GLOF risk.

Methodology

Study area

Langtang Basin is a U-shaped valley with boulders, rock fragments, and debris covering the steep slopes and high plateaus, while forest and grassland are at lower altitudes (Adhikari et al., 2014; Ragettli et al., 2015). The basin extends from a longitude of 85°31'E to 85°48'E and a latitude of 28°08'N to 28°24'N, where 46% of the total basin area is glacierized (Immerzeel et al., 2012; Zhou et al., 2017). The elevation ranges from 3800 m.a.s.l. up to 7234 m.a.s.l. and has an average altitude of 5169 m.a.s.l. with a mean slope of 26.7° (Immerzeel et al., 2012; Pradhananga et al., 2014; Zhou et al., 2017).

The Lirung Glacial Lake, also locally known as Kyanjing Lake, lies at the terminus of the Lirung Glacier, which originates from the Langtang Lirung peak (7,234 meters above sea level). The Langtang valley is a region of glaciological and hydrological interest due to its high-altitude environment, numerous retreating glaciers, and emerging glacial lakes.

Figure 1*Kyanjing meteorological station and Lirung glacial lake**Note:*

A. Kyanjing meteorological station, photograph, and B. Lirung glacial lake and the micro-hydropower operated from the lake.

@D. Pradhananga

Data

The study analyses the extent of Lirung Glacial Lake for the years 2010, 2015, 2020, and 2024 to assess decadal changes and trends in glacial lake dynamics. The study utilizes satellite imagery from two sources to analyze the changes in lake extent. For 2010, Landsat-8 imagery with a spatial resolution of 30 meters was used. For 2015, 2020, and 2024, Sentinel-2 imagery with a higher spatial resolution of 10m was used, allowing for more accurate lake boundaries.

To delineate water boundaries Normalized Difference Water Index (NDWI) was applied. This method is widely used to access and identify water bodies in satellite imagery (Gardelle et al., 2011; Sarp & Ozcelik, 2017; Watson et al., 2018).

$$NDWI_{(Green, NIR)} = (Green - NIR) / (Green + NIR)$$

For Sentinel 2,

$$NDWI = (B03 - B08) / (B03 + B08)$$

For Landsat-8

$$NDWI = (B03 - B05) / (B03 + B05)$$

The glacier outline used for this study is accessed from the ICIMOD Regional Database System. The study area was delineated using the QGIS platform. The satellite imagery used for this study is available at the Sentinel Hub EO Browser. Climate data were analyzed using the bias-corrected WFDEI (WATCH Forcing Data ERA-Interim) reanalysis dataset archived from Pradhananga et al. (2024). Key climate variables, temperature and precipitation, were analyzed for the years 1979 to 2024.

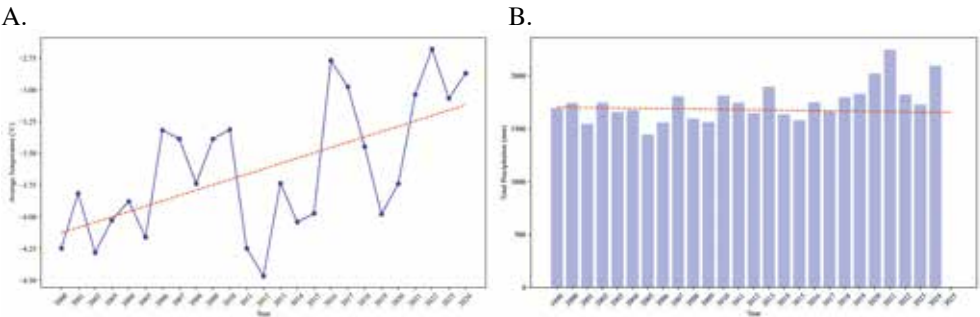
Results

Climate analysis

The analysis of bias-corrected WFDEI data from Kyanjing Station in Langtang Basin (Figure 1) for the period (1979 – 2018) shows significant changes in climatic variables, critical for understanding glacier melt rates. The mean annual temperature, as shown in Figure 2(a), has an increasing rate of 0.0095°C per year with a p-value of 0.0003, suggesting a statistically significant trend. The total annual precipitation depicts a slight negative slope of 0.05mm per year, indicating a very nominal decline in the precipitation trend. However, the p-value of 0.97 implies that the trend is not statistically significant. The precipitation has remained relatively stable over the period of study, even though there is yearly variation, as illustrated in Figure 2(b). These suggest precipitation has not changed significantly; the warming temperature might have caused an impact on glacier melt, snow to rain phase change, causing melting of glaciers, adding water volume to the lake, and increasing its area.

Figure 2

Bias-corrected WFDEI data and precipitation at Kyanjing



Note:

Bias-corrected WFDEI data from Kyanjing Station for Langtang Basin during the period 1979-2018 (a) Mean annual temperature and (b) Total precipitation at Kyanjing

Lake area extent analysis

Table 1, Figures 3 and 4 show that the lake area has increased significantly over the past 14 years. Between 2010 and 2024, the lake area increased by approximately 60.8%, changing from 0.016 km² to 0.064 km². Approximately, the lake has expanded its area by 0.0035 km² per year. The expansion trend in the linear graph of Figure 4 is supported by the remote sensing data from Figure 3. The changes observed are due to climatic conditions and the accelerated glacial melt from the adjacent Lirung Glacier. Further, a high R² = 0.988 value indicates that the data fits the trend well, raising long-term concerns regarding water availability for hydropower generation and downstream communities.

Figure 3

Lirung Lake area evolution over time from 2010 to 2024

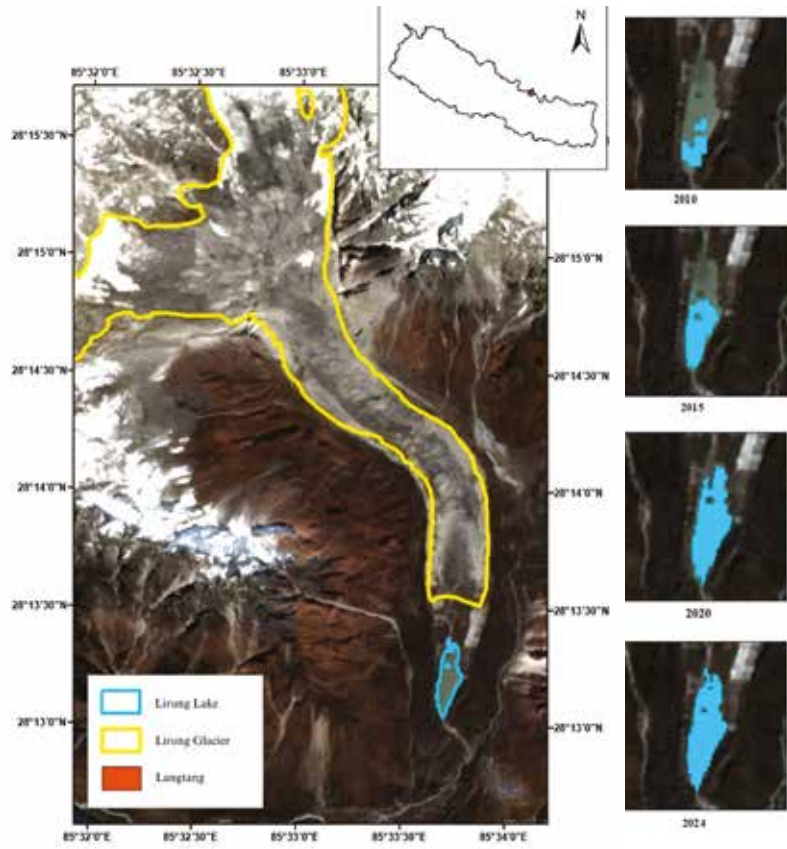


Figure 4

Lirung Lake area change from 2010 to 2024

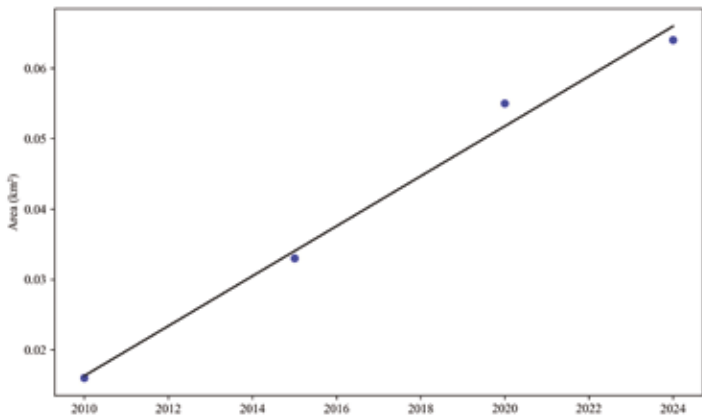


Table 1

Area increased in a certain year

Years	Area (Km ²)
2010	0.016
2015	0.033
2020	0.055
2024	0.064

Discussion

Rapid expansion of Lirung Glacier Lake from 0.016 km² in 2010 to 0.064 km² in 2024 highlights a fourfold increase over just 14 years. Notably, this rate of expansion could further increase in the future, as indicated by the high correlation ($R^2 = 0.988$) value. While this is lower than the basin-wide average of 0.3 km² yr⁻¹ for the Koshi basin, 0.11 km² yr⁻¹ for the Gandaki Basin, and 0.132 km² yr⁻¹ for the Karnali Basin (Khadka et al., 2023). The proportional increase in Lirung’s area is significant and highlights the vulnerability of small, debris-covered glaciers to local climate. Further, under worst-case scenarios, glaciers are predicted to melt by 80%, which will definitely increase the glacier lake area (IPCC, 2023; Khadka et al., 2020; Pradhananga et al., 2024; Prasad et al., 2019).

In the Langtang region of Nepal, glaciers are in a negative mass balance (Khadka et al., 2023). Lirung Glacier downwastes at −1.3 and −1.8 m yr⁻¹ during the study period (1974–2010), increasing water and ice loss from the glaciers, indicating growth in the lake area extent (Nuimura et al., 2017). In this context, our findings of increased lake area of 60.8% appear aligned with the observed melting and thinning rates. Further, Khadka et al. (2018) also reported on a regional scale that the glacial lake areas in the Himalayas of Nepal increased by approximately 25% from 1977 to 2017.

Conclusion

This study reveals a significant expansion of Lirung Glacial Lake in the Langtang Basin between 2010 and 2024. The use of multi-temporal satellite imagery from Sentinel-2 and Landsat 8 revealed a 60.8% increase in lake area over the 14 years, which is closely linked to the rapid retreat of the Lirung Glacier and warming climate, along with variations in precipitation patterns. Earlier satellite records from Landsat before 2010 lacked the spatial resolution necessary to reliably capture small-scale changes, particularly in the early stages of lake development.

Notably, the consistently increasing linear trend in Lirung Lake’s area ($R^2 = 0.99$) suggests continued growth is likely for glacial lake development, heightening the risk of GLOF, which threatens downstream infrastructure, including Nepal’s only glacial-fed micro-hydropower system, as well as local livelihoods and ecosystem stability. To mitigate these emerging hazards and support sustainable water resource use, urgent action is needed. This includes satellite and in-situ monitoring, the implementation of early warning systems for potential GLOF events, and the adoption of integrated water resource management strategies in glacier-fed headwaters. As the impacts of climate change intensify, such proactive measures will be essential to safeguarding both human and environmental systems across the Nepal Himalayas and other vulnerable mountain regions.

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Climate change and the barriers of LAPA implementation

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Abstract

Climate change poses significant challenges to local governance systems, particularly in developing countries where institutional, financial, and social capacities remain limited. Local Adaptation Plans of Action (LAPA) of Nepal represent a pioneering policy framework for integrating climate adaptation into local development planning. However, despite a decade of implementation, substantial gaps persist between policy design and on-ground execution. This study has examined the barriers affecting LAPA implementation in selected municipalities using a qualitative case study approach. Guided by a widely recognized diagnostic adaptation framework, the research draws on semi-structured interviews with municipal officials, local stakeholders, and development practitioners, complemented by document review and thematic analysis. The findings reveal six major categories of interlinked barriers: institutional fragmentation, financial ambiguity, regulatory and legal inconsistency, political interference, attitudinal resistance, and socio-cultural exclusion. These barriers manifest across all phases of the adaptation cycle, understanding, planning, and managing and tend to reinforce one another, creating systemic implementation bottlenecks. For instance, weak institutional coordination contributes to inefficient financial flows, while unclear mandates and elite capture compromise inclusive governance. The study highlights the need for targeted institutional reforms, enhanced budget-policy alignment, regulatory clarity at the subnational level, and stronger engagement with marginalized groups. By illuminating the dynamic interactions among barriers, the study contributes to the understanding of adaptation governance in decentralized contexts and offers policy-relevant insights for improving the effectiveness of local adaptation strategies in Nepal and similar settings.

Keywords: adaptation, barriers, climate change, community, implementation

Introduction

Climate change has emerged as one of the most pressing global challenges, with far-reaching implications for ecosystems, societies, and economies. It has been a critical global issue, evidenced by escalating temperatures and severe weather events like floods, landslides, and droughts (UNDP, 2015). Many climate change studies have shown Nepal as one of the least developed countries vulnerable to climate change, and it's experienced accelerated the glacial melting and heightened disaster risks (Jha & Shrestha, 2013; UNDP, 2015). This change in the environment has a substantial influence on the infrastructure, health, and agriculture sectors, leading to both seasonal and permanent migration across the nation. Nepal has implemented deliberate adaptation measures to reduce these effects and improve resilience as a result (NCCAF, 2012). Launched in 2010 with funding from the Least Developed

Countries Fund, the National Adaptation Plan of Action (NAPA) aims to incorporate climate change considerations into national development objectives (MSFP, 2015; NCCSP, 2012). In a same, decentralized governance and local involvement in adaptation activities are prioritized in the LAPA, which was started in 2011 and updated in 2019 (Maharjan, 2019; GoN, 2011; NCCSP, 2012).

However, the obstacles stand in the way of these adaptation strategies' successful execution in Nepal. The main obstacles are related to capability, planning, and governance (Maharjan, 2019; Regmi & Bhandari, 2013). Complicating matters are socio-cultural elements that impact local decision-making in addition to technical and budgetary limitations (Chanudhury et al., 2014).

This study aims to comprehensively analyze and examine these barriers, examining their characteristics, and assessing their impacts on the implementation of local climate change adaptation plans in Nepal. It specifically aims to respond to the following research question: What are the institutional, financial, legislative and regulatory, and social and cultural barriers encountered in the implementation of local climate change adaptation plans, and its impacts?

Hence, the study is focused to provide insights on the strategies for overcoming barriers and improving the effectiveness of climate adaptation planning in Nepal.

Adaptation barrier

Adaptation barriers are defined as factors that hinder the planning and implementation of adaptation actions or restrict available options (IPCC, 2014; National Research Council, 2010). These obstacles disrupt and slow down adaptation processes, reducing their effectiveness. Overcoming barriers requires coordinated efforts, efficient resource management, innovation, stakeholder engagement, consensus building, option prioritization, and adequate information (Eisenack, et al., 2014). While barriers and limits are sometimes conflated, limits refer to conditions that render adaptation ineffective due to insurmountable factors (Adger et al., 2007), whereas barriers are mutable impediments to adaptation.

Types of barriers

Barriers encompass socio-cultural, institutional, financial, attitudinal, and political dimensions, each presenting unique challenges to effective adaptation planning and implementation.

Cultural and behavioral barriers: These barriers stem from organizational norms, values, attitudes, and practices that influence how institutions perceive and respond to climate-related risks (Burch, 2010). They are particularly evident at the municipal level and shape the adaptation strategies adopted.

Social barriers: Jones (2010) describes social barriers as cognitive, normative, and institutional constraints that hinder the identification of optimal adaptation strategies. Generally, in Nepal, these barriers are intertwined with societal structures such as caste, class, ethnicity, and gender, impacting community resilience to climate impacts.

Structural and operational barriers: These barriers relate to organizational structures and procedures within institutions that influence long-term adaptation policies and practices (Burch, 2010). Issues such as weak governance, insufficient data availability, and fragmented decision-making processes hinder effective adaptation planning.

Regulatory and legislative barriers: This category includes policy tools and legislative frameworks that either facilitate or hinder adaptation planning efforts. Effective climate policies require robust institutional frameworks and clear legal mandates to integrate climate considerations into planning processes.

Contextual barriers: These barriers refer to environmental factors and community values that either support or hinder adaptation actions within local governance structures (Burch, 2010). Understanding these local contexts is crucial for aligning adaptation strategies with community priorities.

Institutional barriers: Eisenack et al. (2014) highlight institutional barriers arising from governance complexities, resource constraints, and inadequate technical capacities within institutions. Fragmented governance and unclear roles among stakeholder's complicate adaptation planning and decision-making processes (Productivity Commission, 2012).

Financial barriers: Financial constraints pose significant challenges to climate change adaptation, limiting resources for long-term planning and implementation (Eisenack, et al., 2014). Insufficient financial resources at the local level often hinder effective management of climate risks and proactive adaptation measures (Productivity Commission, 2012).

Attitudinal barriers: These barriers involve public attitudes, beliefs, and knowledge gaps about climate change, influencing community engagement in adaptation actions (National Research Council, 2010). Addressing attitudinal barriers requires efforts to enhance public awareness and change historical perceptions.

Political barriers: Political will and leadership are critical for advancing climate adaptation agendas, but political barriers such as conflicting interests, policy inertia, and budget constraints can delay effective adaptation planning (Ekstrom & Moser, 2014; Eisenack, et al., 2014). Political commitment is essential for mobilizing resources and creating supportive environments for local climate action.

Table 1

Phases and barriers in the stage of implementation of managing phase

Phases & process stage: planning	Barriers	Typologies
Implement Options	• Threshold of intent • Authorization • Sufficient resources (fiscal, technical, etc.) • Accountability • Clarity/specificity of option • Legality and procedural feasibility • Sufficient momentum to overcome institutional stickiness, path dependency and behavioral obstacles	• Financial • Institutional • Legislative and regulatory barriers

Source: Moser & Ekstrom, 2010.

Table 1 illustrates the phases and barriers during the implementation stage of the managing phase. In this phase, key barriers include financial constraints, institutional hurdles, and

legislative and regulatory complexities. These barriers pose challenges such as securing sufficient resources, navigating legal requirements, and overcoming institutional inertia and behavioral obstacles. The ability to implement adaptation options hinges on factors like clear intent, sufficient funding, and the emergence of new stakeholders actively involved in executing adaptation plans (Moser & Boykoff, 2013). For example, in Zimbabwe, farmers' reluctance to engage in adaptation actions due to lack of climate knowledge underscores the critical role of intent in implementation. Successful cases, like the Albay Province in the Philippines, highlight how overcoming these barriers requires a robust transition from planning to effective implementation of climate change action programs (Mimura, et al., 2014).

Review of literature

Climate change adaptation planning has received growing global attention as climate-induced risks intensify across socio-ecological systems. In developing countries like Nepal, institutional, financial, legislative, and socio-cultural challenges often hinder the implementation of adaptation policies at the local level. This section reviews existing literature relevant to the implementation of local climate change adaptation strategies, focusing particularly on the LAPA, and situates the present study within broader scholarly and policy debates.

Adaptation to climate change is broadly classified as anticipatory or reactive, and as autonomous or planned (Klein et al., 2007; Fussel, 2007). Autonomous adaptation often occurs at the level of individuals or households without formal policy guidance, whereas planned adaptation is typically initiated by governments or institutions in anticipation of projected climate impacts (Adger et al., 2007). Planned adaptation is more structured and linked to development planning processes, particularly in developing countries where vulnerabilities are higher and resources more constrained (Mimura et al., 2014).

However, the effectiveness of planned adaptation is highly contingent on institutional frameworks, governance structures, and local capacity. The Intergovernmental Panel on Climate Change (IPCC, 2014) emphasizes that adaptation responses are shaped by governance systems that influence the enabling or constraining environment for implementation. This aligns with the diagnostic framework proposed by Moser and Ekstrom (2010), which identifies barriers in three sequential phases—understanding, planning, and managing—each containing institutional, informational, financial, cultural, and political dimensions. Their framework has been influential in shifting attention from technical limitations to the broader social and institutional landscape that shapes adaptation outcomes.

In the context of Nepal, adaptation planning has evolved through several key national initiatives, including the National Adaptation Programme of Action (NAPA), the Climate Change Policy (2019), and subsequently, the LAPA framework (GoN, 2019). LAPA, in particular, emphasizes decentralized and community-driven planning approaches, aiming to embed climate resilience in local development processes (Maharjan, 2019). While the LAPA framework represents a shift from top-down to bottom-up adaptation governance, multiple studies have revealed implementation bottlenecks.

Dhungana et al. (2017) assessed the initial phase of LAPA implementation and found significant gaps in institutional coordination and local consultation. They argued that insufficient integration of local knowledge, lack of clarity in roles among stakeholders, and

poor accountability mechanisms weakened the framework's effectiveness. These findings resonate with Moser and Ekstrom's (2010) "managing phase" barriers, particularly around institutional inertia and leadership deficits.

Maharjan (2019) further highlights how political interests often override climate objectives in local planning processes. For example, development projects such as road construction receive higher prioritization than long-term climate adaptation measures. This reflects the kind of political and attitudinal barriers emphasized by Eisenack et al. (2014), where misaligned incentives and short-term political gains can distort adaptation priorities.

Similarly, Regmi and Bhandari (2013) explored institutional capacity challenges in Nepal's adaptation landscape, underscoring the disconnect between national adaptation frameworks and local governance readiness. They argued that despite the proliferation of policies, effective adaptation requires functional local institutions, trained personnel, and delineated mandates, a theme echoed by Smith et al. (2009) in their broader assessment of adaptation governance.

Internationally, the literature reflects similar patterns. Biesbroek et al. (2013) argue that adaptation is often constrained not by lack of knowledge or technology, but by institutional fragmentation, unclear responsibilities, and lack of coordination across governance levels. This is also evident in Australian and European contexts, where local governments struggle to reconcile sectoral mandates and limited funding with climate responsibilities (Bauer et al., 2012; Baker et al., 2012).

The lack of adaptive capacity at the local level is a recurring theme. For example, studies by Carmin et al. (2012) and Gero et al. (2012) show that although local governments are central to climate resilience, they often face funding limitations, technical gaps, and overlapping mandates. These issues are mirrored in Nepal's experience with the LAPA, particularly in remote districts where institutional presence is weak and financial flows are inconsistent.

The literature also points to the underutilization of indigenous knowledge and social capital in adaptation planning. In Nepal, the marginalization of traditional practices, such as indigenous seed varieties and community-based farming systems, has been identified as a significant social and cultural barrier (Chaudhury et al., 2014; Jones, 2010). Despite policy mandates on gender and inclusion, practical implementation often overlooks the decision-making roles of women and disadvantaged groups.

While the existing literature identifies various typologies of barriers, ranging from institutional and financial to socio-cultural and political, few studies provide a structured analysis of how these barriers interact across different phases of adaptation planning. The present study addresses this gap by using the Moser and Ekstrom (2010) framework to examine the LAPA implementation challenges through an integrated lens. This approach enables a deeper understanding of not only the types of barriers but also their relationships and cumulative impacts on the ground.

In sum, while substantial literature has examined the constraints to adaptation, there remains a need for grounded, empirically informed studies that integrate theory with practice. This research contributes to addressing this need by providing an evidence-based assessment of the barriers to the LAPA implementation in Nepal, highlighting the interdependence of institutional, financial, legislative, social, political, and attitudinal factors.

Global perspectives on climate change adaptation

Globally, climate change adaptation has emerged as a policy and research priority due to the escalating intensity and frequency of climate-related hazards. International frameworks such as the United Nations Framework Convention on Climate Change (UNFCCC) and its offshoots, including the NAPAs, have been instrumental in guiding adaptation priorities in developing countries (UNFCCC, 2021). The Paris Agreement further reinforced the commitment to adaptation by placing it on equal footing with mitigation, emphasizing the role of countries in planning and implementing context-specific adaptation strategies (Magnan & Ribera, 2016).

However, literature indicates that while global policy frameworks provide high-level direction, their translation into national and sub-national planning often faces significant contextual challenges (Biesbroek et al., 2013). These include resource constraints, institutional misalignments, and varying degrees of governance capacity. The current study echoes these issues, particularly in the Nepali context, where adaptation plans like LAPA have struggled to align global priorities with local realities due to governance and resource barriers.

Understanding adaptation to climate change

Adaptation refers to the process of adjustment in human or natural systems in response to actual or expected climate stimuli or their effects (IPCC, 2014). It can be anticipatory or reactive, autonomous or planned. Planned adaptation, which is policy-driven and structured within formal institutions, is often necessary in contexts with high vulnerability and limited adaptive capacity, such as Nepal (Adger et al., 2007; Klein et al., 2007).

Planned adaptation is particularly relevant for the implementation of LAPA, which represents a strategic intervention to incorporate climate risks into local development planning. However, as identified in Moser and Ekstrom's (2010) diagnostic framework, barriers at each stage of the adaptation cycle, which are understanding, planning, and managing, can inhibit effective implementation. This study applies that framework to examine how different types of barriers manifest within the LAPA context and influence adaptation outcomes.

National initiatives in Nepal

Nepal has taken several steps to institutionalize climate adaptation planning, beginning with the NAPA in 2010, followed by the Climate Change Policy (2019), and later, the LAPA introduced in 2011 and revised in 2019 (Government of Nepal, 2011). These initiatives aim to mainstream climate considerations into local governance and development processes.

Despite these efforts, adaptation planning in Nepal remains challenged by fragmented institutional roles, insufficient local capacity, and inadequate funding (Regmi & Bhandari, 2013; Maharjan, 2019). Moreover, adaptation is often deprioritized in favor of conventional development projects, reflecting political barriers that undermine strategic climate action (Dhungana et al., 2017). The present study provides empirical validation of these observations by documenting field-level implementation challenges faced by the LAPA actors.

Local government roles in adaptation

Local governments are the key actors in the adaptation landscape, especially in decentralized systems like Nepal. They are tasked with translating national policies into tangible local

actions that reflect community needs and vulnerabilities (Hamin & Gurrán, 2009). The LAPA was designed with this principle in mind, promoting community-led adaptation planning and local decision-making. However, as Gero et al. (2012) and Carmin et al. (2012) highlight, local authorities often face institutional constraints, lack technical knowledge, and have minimal financial autonomy, which are observed cases in Nepal.

Challenges to climate adaptation governance

Effective adaptation governance involves the coordination of multiple actors across levels of government, sectors, and communities. Key challenges include policy fragmentation, unclear mandates, weak institutional capacities, and the lack of sustained political will (Eisenack et al., 2014; Biesbroek et al., 2013). These challenges are not just structural but are also embedded in cultural, behavioral, and attitudinal dimensions that influence how climate risks are perceived and prioritized (Moser & Boykoff, 2013). In Nepal, these governance challenges are particularly acute in remote and rural municipalities where adaptation is often externally funded and not embedded into the regular planning framework (Regmi et al., 2016).

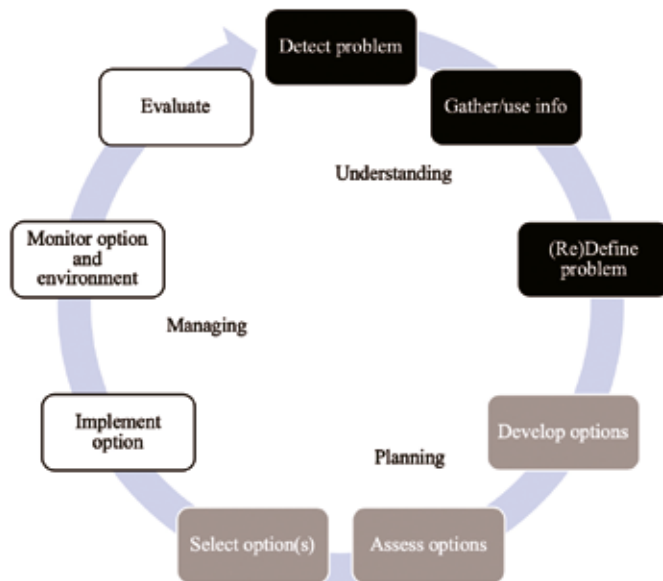
Conceptual framework

This study employs a diagnostic approach to investigate the barriers that hinder the implementation of the LAPA in Nepal. The conceptual framework is primarily informed by Moser and Ekstrom's (2010) analytical model, which is designed to identify, categorize, and interpret the various types of barriers that hinder climate change adaptation efforts. Their framework is particularly suitable for this study as it not only categorizes barriers by type, such as institutional, informational, financial, social, and political, but also locates them within different phases of the adaptation process: understanding, planning, and managing.

In this framework, barriers are defined as conditions or factors that impede the initiation, design, or execution of adaptation strategies, thereby constraining decision-making or implementation (Moser & Ekstrom, 2010). Importantly, barriers are not conceptualized as insurmountable "limits," but rather as challenges that can be addressed or overcome through appropriate intervention, coordination, or reform (Adger et al., 2007).

Moser and Ekstrom (2010) framework is applied to analyze qualitative data collected from stakeholders involved in the LAPA implementation in Nepal. Each identified barrier type whether institutional, financial, legislative, socio-cultural, political, or attitudinal is examined in terms of its location in the adaptation cycle and its functional interaction with other barriers. For example, weak institutional capacity is understood not merely as a discrete issue but as a constraint that cascades into ineffective financial planning and limited regulatory enforcement. Similarly, attitudinal and political barriers are considered to influence both the threshold of intent and stakeholder commitment, which are pivotal for practical implementation in the managing phase of adaptation.

Figure 1 below conceptualizes how these barriers interact in the adaptation planning process, as adapted from Moser and Ekstrom (2010). The outer structure represents the three sequential phases of adaptation: understanding the problem, planning responses, and managing implementation. Within each phase, specific categories of barriers are nested. For instance, informational and cognitive limitations are more likely to arise during the understanding phase, while financial and regulatory constraints dominate the planning and managing stages.

Figure 1*Different phases and process of adaptation**Source: Moser & Ekstrom, 2010*

The framework also accommodates cross-cutting and interacting barriers. For instance, institutional inertia defined by staff turnover, weak leadership, and fragmented mandates not only impedes planning but also undermines the sustainability of implementation. Similarly, financial ambiguity often reflects deeper regulatory and institutional gaps. By structuring the analysis through this diagnostic lens, the study not only identifies the most prominent barriers but also reveals their interconnectedness and cumulative effects.

Methods and materials

This study employed an exploratory qualitative design to investigate the barriers encountered during the implementation of the LAPA in Nepal. An exploratory approach was appropriate, given the limited prior research on how diverse barriers interact at the local level, which allowed for an in-depth understanding of stakeholder perspectives and contextual dynamics (Moser & Ekstrom, 2010). The research design facilitated a comprehensive examination of institutional, financial, legislative, regulatory, socio-cultural, political, and attitudinal factors influencing the LAPA implementation.

Participants were recruited through a combination of convenience and snowball sampling. Initially, convenience sampling identified the LAPA practitioners and local government officials who were readily accessible and met predefined inclusion criteria, such as having direct involvement in the planning or execution of the LAPA activities. Following these initial interviews, snowball sampling was employed to identify additional stakeholders with relevant experience or insights; early interviewees provided referrals to other key informants (Noy, 2008). This two-pronged strategy was essential given the decentralized and context-

specific nature of the LAPA implementation, where individuals with pertinent knowledge are not uniformly distributed across districts. Although this sampling approach limits statistical generalizability, it enabled the purposeful identification of those most knowledgeable about implementation challenges. To mitigate potential sampling bias, interviews were conducted across four distinct districts, Humla, Jumla, Rukum, and Kathmandu, ensuring a range of geographic, institutional, and socio-cultural contexts were represented.

Primary data were collected between February and April 2024 via semi-structured interviews. A total of forty stakeholders participated, including the LAPA officials, representatives from local government offices, committee members, and climate adaptation experts. Each interview lasted between 45 and 60 minutes and followed a predeveloped interview protocol designed to probe perceptions of various barriers (institutional, financial, legislative/regulatory, socio-cultural, political, and attitudinal). Field notes were taken during face-to-face interviews, and all sessions were audio-recorded with participant consent. Secondary data comprised official the LAPA guideline documents, policy reports, and progress reviews obtained from the Ministry of Forests and Environment (MoFE) and the Nepal Climate Change Support Programme (NCCSP). These documents were reviewed to triangulate stakeholder accounts and enhance the robustness of barrier identification.

Data analysis adopted a thematic analysis framework, drawing on the principles outlined by Braun and Clarke (2006) and the diagnostic framework of Moser and Ekstrom (2010). Analysis proceeded through six iterative phases: (1) familiarization with raw data by repeatedly reading transcripts and field notes; (2) generation of initial codes by highlighting meaningful data segments related to barrier types; (3) identification of candidate themes by clustering codes according to Moser and Ekstrom's typologies (e.g., institutional, financial, legislative/regulatory, socio-cultural, political, attitudinal); (4) review and refinement of themes to ensure coherence and representativeness; (5) definition and naming of finalized themes with clear operational definitions; and (6) production of a comprehensive thematic narrative linking barrier characteristics to implementation outcomes (Braun & Clarke, 2006; Moser & Ekstrom, 2010). Coding was performed manually, with cross-checking by two researchers to enhance reliability. Discrepancies in code application were resolved through discussion until complete consensus was reached.

To minimize researcher bias, several measures of trustworthiness were employed. First, methodological triangulation compared interview findings with documentary evidence (e.g., LAPA guidelines, NCCSP reports) to validate and contextualize stakeholder assertions. Second, reflexive journaling was maintained throughout data collection and analysis to record researcher insights, assumptions, and potential influences on interpretation. Third, member checking was conducted by sharing preliminary thematic summaries with five purposively selected participants to confirm the accuracy of representation and interpretation. Finally, an audit trail documented all steps from data collection through final analysis, ensuring transparency and replicability (Miller & Brewer, 2003; Maxwell, 2012).

Ethical considerations were carefully observed. Informed consent was obtained from all participants before conducting interviews. Participants were assured of anonymity and confidentiality, and data were securely stored to maintain privacy and data integrity.

General information of respondents

Out of the total 40 respondents, the majority interviewed were from the LAPA including

experts, coordinators, executive members were altogether 25, whereas local government officials and administrative assistants were 12 and 3 respectively. The information from respondents was also verified by experts, including the NCCSP employees and Ministry of Forest and Environment (MoFE) representatives.

Similarly, the working experiences of the respondents were varied working in the climate change adaptation projects. Out of the 40 respondents, the dominated group has 4-6 years of 13 respondents, followed by 10 respondents with over 6 years, 8 with 2-4 years, and 9 with less than one year of experience.

Findings

This section presents the findings of the study, focusing on the barriers encountered during the implementation of the Local Adaptation Plans of Action (LAPA) in selected districts of Nepal. The discussion is structured around key themes such as institutional, financial, legislative and regulatory, socio-cultural, attitudinal, and political barriers and is interpreted using Moser and Ekstrom's (2010) diagnostic framework.

Implementation modality of the LAPA

Implementation of the LAPA activities focus on thematic areas such as natural resource management, climate-friendly infrastructure, and watershed management. The LAPA framework emphasizes three guiding principles: enhancing climate resilience, making infrastructure resilient, and promoting adaptation and disaster risk reduction practices through community participation.

Barriers encountered in the LAPA implementation

Barriers encountered during the LAPA implementation were categorized into institutional, financial, legislative, regulatory, and socio-cultural barriers. Institutional barriers included lack of capacity among executive committee members, absence of specialized focal persons, high staff turnover, and delays due to seasonal and logistical challenges. Coordination issues between stakeholders, gender and social inclusion gaps, and bureaucratic delays further hindered effective implementation.

Institutional barriers

Institutional barriers emerged as the most frequently reported and structurally pervasive challenge across all study sites. These included a lack of dedicated climate adaptation focal persons, frequent staff turnover, poor documentation and knowledge transfer, and limited technical capacity at the municipal level. According to Moser and Ekstrom (2010), such constraints are characteristic of the "managing" phase of the adaptation process, where institutional inertia and weak leadership hinder transition from planning to implementation.

The research found that the LAPA executive committees often lacked technical expertise and continuity. The absence of institutional memory due to rapid staff changes meant that adaptation plans were inconsistently implemented or delayed. These findings align with Dhungana et al. (2017), who noted similar institutional discontinuities in local adaptation processes in Nepal. Additionally, coordination gaps between national and local authorities led to inconsistent support, duplications in planning efforts, and unclear lines of accountability, a phenomena also described in the context of other developing countries (Eisenack et al., 2014).

Financial barriers

Financial constraints were widely acknowledged by stakeholders, not only in terms of funding volume but also in terms of procedural clarity and sequencing. Respondents reported that the LAPA budgets were allocated without comprehensive planning, resulting in mismatches between financial flows and implementation priorities. As Moser and Ekstrom (2010) suggest, adaptation efforts often fail when there is a threshold of intent but insufficient resources to operationalize planned interventions.

Budget allocation mechanisms remained unclear, especially regarding what constituted management versus programmatic expenses. Several interviewees noted that budget ceilings were often rigid and failed to accommodate local infrastructure needs, echoing Regmi and Bhandari's (2013) observation that national budgeting processes do not sufficiently reflect bottom-up planning. Furthermore, delays in disbursement of funds affected project sequencing, reducing both efficiency and stakeholder confidence in adaptation planning.

Legislative and regulatory barriers

The absence of localized climate adaptation legislation or operational guidelines tailored for the LAPA was a significant constraint. While the Climate Change Policy (2019) offers strategic direction, respondents noted the lack of district-level by-laws or implementation directives. This regulatory vacuum hampered the institutionalization of the LAPA within municipal planning frameworks.

This finding reflects the “authorization” and “legal feasibility” bottlenecks identified by Moser and Ekstrom (2010) during the planning and managing phases. The gap between national frameworks and local legal instruments is not unique to Nepal; similar difficulties have been reported in decentralized adaptation settings in sub-Saharan Africa (Antwi-Agyei et al., 2015). In addition, traditional and indigenous practices were rarely integrated into planning regulations, despite their potential relevance for locally appropriate adaptation.

Socio-cultural barriers

Social norms, gender roles, and caste hierarchies were frequently mentioned as underlying factors that constrained inclusive adaptation planning. Despite the mandatory provision for 33% female representation in executive committees, many respondents indicated that women and marginalized groups remained largely symbolic participants in decision-making. This dynamic reflects both normative and behavioral barriers, which are deeply rooted in Nepal's socio-political structure.

Jones and Boyd (2011) argue that such social barriers, manifesting as limited participation, reduced voice, and institutional exclusion, can critically undermine the legitimacy of adaptation and its outcomes. The current findings reinforce that view, particularly in remote districts where literacy gaps and traditional power structures further impede inclusive engagement. Notably, reluctance to adopt indigenous crops or water practices was also linked to socio-cultural preferences shaped by modernization narratives promoted through donor-led interventions.

Attitudinal and political barriers

Attitudinal barriers were particularly evident in the form of apathy among local bureaucrats

and elected officials, some of whom viewed climate adaptation as a peripheral rather than core development agenda. This perception influenced resource allocation decisions and undermined political ownership of adaptation interventions. The absence of dedicated climate adaptation departments at the municipal level further diluted administrative responsibility and interest.

Political barriers were also present in the form of elite capture, wherein politically connected individuals influenced adaptation funds and project decisions. As observed by Maharjan (2019), adaptation priorities often lost ground to more visible infrastructure projects, especially in pre-election contexts. These observations align with the “threshold of intent” and “stakeholder commitment” barriers in Moser and Ekstrom’s (2010) framework, where weak political will impedes adaptive transitions.

Synthesis and interactions between barriers

Notably, the study revealed that these barriers do not operate in isolation. Rather, they are interrelated and mutually reinforcing. For instance, weak institutional capacity often leads to inefficient financial management, while regulatory ambiguity amplifies attitudinal apathy by making accountability less clear and diffuse. Political interference further exacerbates institutional and financial barriers by distorting priorities.

Such interactions support Eisenack et al.’s (2014) argument that adaptation barriers should be understood as “systemic” rather than discrete. The present study contributes to this line of thinking by demonstrating how institutional fragmentation, fiscal ambiguity, and social exclusion collectively produce an environment in which adaptation plans like the LAPA are neither wholly owned nor sustainably implemented.

These findings suggest that the LAPA framework provides a structured entry point for community-level adaptation, its implementation is undermined by a combination of systemic and localized barriers. Addressing these challenges requires an integrated approach that goes beyond technical interventions to include institutional reform, political engagement, and regulatory innovation.

Discussion

The study aimed to investigate the barriers that hinder the effective implementation of the LAPA in Nepal, drawing on stakeholder perspectives and structured through the diagnostic framework of Moser and Ekstrom (2010). The findings reveal that these barriers are not isolated phenomena but interrelated, dynamic, and embedded within institutional, regulatory, socio-cultural, political, and behavioral systems. This section discusses how the empirical insights extend existing literature, confirm prior observations, and generate new understanding of climate adaptation governance in developing country contexts.

Consistent with earlier studies (Regmi & Bhandari, 2013; Dhungana et al., 2017), this research confirms that institutional barriers such as staff turnover, lack of climate focal units, and fragmented mandates that remain central challenges to adaptation implementation in Nepal. However, by applying Moser and Ekstrom’s (2010) framework, this study further demonstrates that these institutional gaps are not merely operational issues but represent deeper deficiencies in adaptive capacity and system-level governance. Specifically, institutional inertia within the “managing” phase of the adaptation cycle obstructs the translation of plans into practical on-the-ground actions.

Similarly, financial constraints are well-documented in climate adaptation literature (Biesbroek et al., 2013; Antwi-Agyei et al., 2015). This study contributes a more precise explanation of how fiscal ambiguity, particularly the lack of alignment between budget cycles and project readiness, undermines the execution of local adaptation priorities. This echoes Moser and Ekstrom's (2010) notion of the "threshold of intent," whereby adaptation is deprioritized when administrative and financial systems are misaligned.

A more nuanced contribution of this study lies in its exploration of socio-cultural and attitudinal barriers. As noted by Jones and Boyd (2011), structural social exclusion based on gender, caste, and ethnicity can significantly distort adaptation outcomes. In the context of Nepal, this research found that while formal provisions for inclusion exist, informal power dynamics often limit meaningful participation of marginalized groups in the LAPA planning and execution. Moreover, the study identifies a perception gap: local officials often perceive adaptation as an external, donor-driven agenda, which reduces internal motivation and accountability.

Political barriers particularly elite capture and project politicization—also surfaced as key obstacles. These findings reinforce Maharjan's (2019) observations that visible infrastructure projects are often prioritized over less tangible adaptation measures, especially during pre-election periods. Political disinterest, when coupled with regulatory ambiguity, weakens the implementation environment and erodes local ownership. These patterns affirm the systemic nature of adaptation barriers described by Eisenack et al. (2014), in which structural, cognitive, and procedural challenges interact across governance levels.

The study finds that these barriers are not discrete but mutually reinforcing. Institutional weakness undermines financial accountability; weak regulatory frameworks permit political interference; socio-cultural exclusion erodes the legitimacy of participatory processes. Such interlinkages demonstrate that adaptation planning cannot succeed without addressing the whole ecosystem of implementation constraints.

Conclusion

This study examined the barriers that constrain the implementation of the LAPA in Nepal, drawing on stakeholder perspectives and interpreting findings through Moser and Ekstrom's (2010) diagnostic framework. The research highlights that institutional fragmentation, financial ambiguity, weak regulatory mandates, socio-cultural exclusion, attitudinal indifference, and political interference collectively undermine the goals of decentralized climate adaptation.

The study contributes to the literature by illustrating how these barriers not only exist independently but also interact systemically across the adaptation process. For instance, weak institutional capacity exacerbates financial inefficiencies, while regulatory uncertainty facilitates elite capture and political misdirection. These insights emphasize that adaptation planning cannot be treated as a technical task alone but must be situated within a broader governance and social context.

From a policy perspective, several recommendations emerge. First, institutional reforms are needed to establish dedicated climate focal points at the municipal level with stable staffing and technical training. Second, budgeting procedures should be aligned with bottom-up planning to ensure flexible, timely, and accountable financial flows. Third, legal instruments

at the subnational level must be clarified to enable the LAPA institutionalization within municipal governance systems. Fourth, efforts to improve inclusivity should extend beyond quotas and focus on capacity-building and leadership development among marginalized groups.

Lastly, fostering political commitment through sustained advocacy and embedding climate adaptation within national development planning processes can help overcome attitudinal and political barriers. Strengthening vertical coordination between federal, provincial, and local governments is also essential to ensuring that adaptation planning is both participatory and effective.

While the study was limited by geographic scope and the availability of respondents during the COVID-19 pandemic, the findings offer valuable insights for other least developed and climate-vulnerable countries facing similar governance and implementation challenges. Future research may expand on this work by applying mixed-methods approaches across diverse ecological and administrative regions in Nepal, or by conducting longitudinal assessments of the post-LAPA revisions.

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From trade routes to trekking trails: A comparative assessment of livelihood capitals among Sherpa households in the Everest (Khumbu) region of Nepal

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Abstract

This paper presents comparative analysis of the livelihood capitals of Sherpa households in Nepal's Everest (Khumbu) region, with a focus on their livelihood adaptation, diversification strategies, and resilience over a period of about seventy years. This timeline is marked by significant changes following Nepal's democratic transition in 1951 and the first ascent of Mount Everest in 1953, which led to the rapid expansion of tourism—now a major contributor to the local as well as national economy. Using case studies of two Sherpa villages—Namche Bazar and Thulo Gumela—this research examines the differences in the state of livelihood capitals between households located along the main tourist trail to Everest Base camp and those in more remote areas. The research is based on household survey data gathered from sixty male and female Sherpa participants, with balanced representation across all age groups in both villages. Findings reveal that Sherpa households have developed diverse strategies to navigate shifting economic, political, and environmental contexts. An analysis of livelihood capitals based on a five capital model as defined in the DFID's Sustainable Livelihood Framework (SLF) shows that Namche households effectively leverage financial capital to enhance other forms of livelihood capital, while Thulo Gumela also demonstrates effective resource management despite having lower levels of human, financial, and physical capital. This study provides essential insights for relevant authorities and stakeholders seeking to improve sustainable livelihood outcomes for both on-route and off-route villages in Khumbu. It underscores the need for strategies that promote conservation within the Sagarmatha National Park and its buffer zone while fostering economic growth and community development.

Keywords: livelihood, Namche, Sherpa, Thulo Gumela, tourism

Introduction

The Sherpa, or *Adivasi Janajati*, is one of Nepal's fifty-nine indigenous communities, making up approximately 0.45% of the country's population of 29.16 million (Maharjan & Maharjan, 2017; Sherpa & Wengel, 2023). The Solukhumbu District, including the Khumbu region, is home to 17,878 Sherpas. Present day Sherpa of Khumbu are believed to be descendants of Tibetan migrants from the Kham region who began to settle in this area about five to six centuries ago (National Statistics Office [NSO], 2021). Sherpas' cultural and religious practices emphasize resource conservation and innovative land use shaped by local knowledge (Sherpa, 2016). Known for their resourcefulness in harsh climatic conditions, Khumbu Sherpas have historically relied on natural resources and transhumant pastoralism for their livelihoods, alongside subsistence farming (Ortner, 2001). In the early 1800s, bartering trade with Tibetans and Indians emerged as an additional income source (Bhattacharai, 2021; Stevens,

1996). Later the first ascent of Mount Everest in 1953 marked the beginning of tourism as a new economic avenue for Khumbu residents (Nepal, 2015). Consequently, the Sherpa economy has evolved through three phases: reliance on natural resources and agropastoral activities; bartering trade; and tourism—though agropastoral activities have remained a secondary livelihood throughout these transitions. The livelihoods of the Sherpa community, along with their evolving challenges, have been profoundly influenced by political and institutional changes in Nepal over the centuries (Sherpa & Wengel, 2023). The advent of democracy in 1951 was a crucial turning point following the end of the 104-year Rana regime (Aryal, 2016; Pawson et al., 1984; Ripert et al., 2009). This new government adopted an open-door policy, permitting foreign visitors to enter Nepal officially for the first time, which led to the inaugural ascent of Mount Everest and sparked the tourism activities in the Khumbu region. However, it took several decades for Everest tourism to become integral to the local economy (Fisher, 1990; Nepal, 2015; Rai, 2017). The influx of visitors notably increased after the construction of the Lukla airstrip in 1964 (Fisher, 1990; Nyaupane & Chhetri, 2009), significantly reducing travel time from Kathmandu to Khumbu from two weeks to a mere 45-minute flight (Stevens, 1993). The establishment of Lukla Airport and Sagarmatha National Park (SNP) in 1976, recognized as a UNESCO World Heritage Site in 1979, were pivotal in enhancing visitor numbers (Fisher, 1990; Nepal, Mu, & Lai, 2020; Rai, 2017).

Tourism is now Khumbu's primary economic driver, with most households relying on it for income (Nepal, Mu, & Lai, 2020; Nyaupane, Lew, & Ttasugawa, 2014). What started as mountaineering, later evolved into trekking, is now popular as "Everest tourism" (Nepal, 2015). Several studies (Fisher, 1990; Miller, 2017; Nepal, Mu, & Lai, 2020; Rai, 2017; Sherpa, 2012) have shown that tourism revenue has greatly improved living standards for many Sherpa families. However, there is limited empirical data on which villages in the region experience the most significant positive or negative impacts of tourism. On the other hand, the studies by Stuart (2024), Singh et al. (2020), Jaquemet (2017), Spoon (2008), Nepal (2002), and Stevens (1996) demonstrate a decline in traditional agro-pastoral practices due to tourism, while climate change research (Faulon & Sacarea, 2020; Nepal, 2011, 2015; Sherpa, 2014) warns of growing social and economic disparities without sustainable livelihoods. that the rise of Everest tourism has led to a noticeable decrease in the Sherpa community's involvement in traditional agro-pastoral practices, signaling a major shift in their way of life. Other studies (Adams, 1992; Gioli et al., 2019; Lama, Becker, & Bergström, 2019; Pandey & Bardsley, 2015; Rayamajhi & Manandhar, 2020; Wyss et al., 2022) have examined Himalayan social-ecological systems, mountain livelihoods, and adaptation strategies to understand community resilience in the face of growing socioecological challenges. Most existing studies on Khumbu focus on major settlements along the main route of the region like Lukla, Namche, and Khumjung, overlooking remote villages. Particularly, a significant gap exists in understanding the impacts of Everest tourism on Sherpa communities in remote villages. Against this backdrop, this study aims to explore the impact of Everest tourism on Sherpa livelihood systems through a comparative study of the villages, located along the main route to Everest Base camp (Namche Bazar) and the one located off this primary route (Thulo Gumela). It examines economic, sociocultural, and environmental aspects of livelihoods to identify key drivers of transformation and the state of livelihood capitals (Knutsson & Ostwald, 2006; Levine, 2014). Understanding these drivers clarifies how they shape livelihood systems and support adaptation and resilience. Using DFID's Sustainable Livelihood Framework, the study applies a comprehensive approach to assess the five forms of livelihood capital among Khumbu Sherpa households.

This research focuses on a period of about 70 years, beginning with the advent of Nepal's first democracy in 1951 that opened the region to tourism. Notably, while the study villages share similar cultural and geographic contexts, their access to tourism and income opportunities differs based on proximity to the main trail and thus varying access to local tourism initiatives and income generating opportunities. The research also explores how tourist behavior and changing tourism trends impact livelihood capitals, offering policy insights to promote equitable growth and long-term sustainability for both on-route and off-route villages.

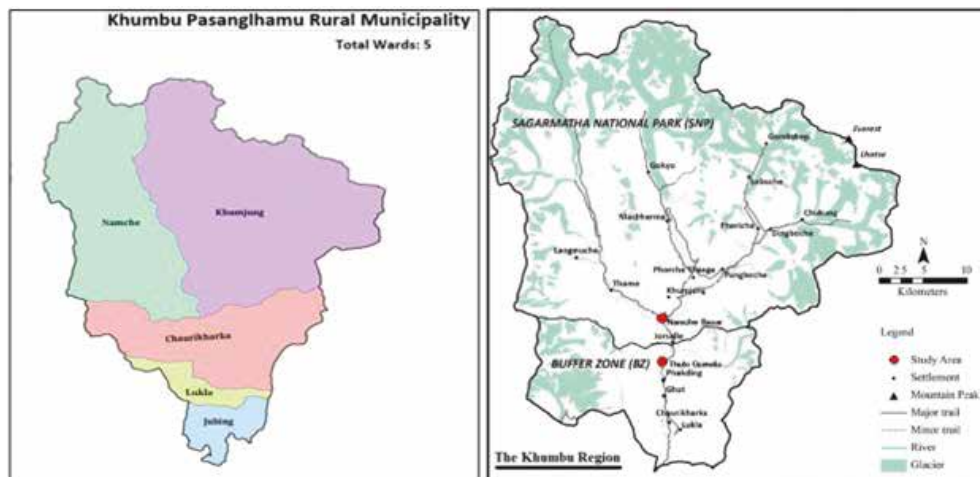
Material and methods

Study sites

The study villages are Namche Bazar and Thulo Gumela, situated in the Khumbu region of Solukhumbu district in Nepal. This area is geographically defined by the coordinates $86^{\circ}31' - 86^{\circ}58'$ East Longitude and $27^{\circ}47' - 28^{\circ}71'$ North Latitude.

Figure 1

Maps of study sites



Note:

Maps showing five wards of Khumbu Pasanglhamu Rural Municipality (L) and the study sites- Namche Bazar and Thulo Gumela (R)

Source: Bhattarai (2021)

Namche Bazar

Namche Bazar situated in Sagarmatha National Park at an altitude of 3,440 meters, is the gateway to Mount Everest and the cultural hub of the Sherpa community (Sinanan, 2022). This bowl-shaped village, home to approximately 200 households, lies just half a kilometer below the SNP headquarters (Bhattarai, 2021). It attracts numerous visitors during the autumn and spring tourist seasons, offering stunning views of peaks like Mount Everest and Mount Amadablam. Historically a trading center, Namche has evolved into a marketplace driven by tourism, shifting from traditional sales of Tibetan artifacts to retail goods such as imported

foods and trekking equipment. Unlike other Khumbu villages, it features modern amenities including electricity, piped water, telecommunications, health posts, banks, and schools. Visitors can explore Sherpa culture through significant sites like a monastery and stupa, along with two museums: one focusing on Sherpa culture and another detailing Khumbu's history.

Thulo Gumela

Thulo Gumela is a quaint village located in the Buffer Zone of Sagarmatha National Park at an elevation of approximately 2,700 meters, about 800 meters below Namche Bazar. Situated one kilometer away from TokTok near Phakding—an acclimatization stop for trekkers—Thulo Gumela consists of thirty Sherpa households and five non-Sherpa blacksmith families, totaling around 100 residents (Bhattarai, 2021). The village, surrounded by verdant hills and snow-capped mountains, features painted mani walls along its trails and is home to the Pema Choling Monastery, a cultural hub for local Sherpa communities. Agriculture is the primary source of livelihood for the residents of this village, although some engage in seasonal tourism activities and construction work. Access to public services is limited due to remoteness; children must walk to neighboring villages for school, and residents travel to Phakding or Tok-Tok to buy essential household goods. For larger purchases, they often go to Salleri, the capital of Solukhumbu or Kathmandu, where prices are comparatively lower.

Data collection and analysis

This research is based on a descriptive design and employs a mixed-methods approach, combining primary and secondary data. Primary data were collected through a household survey of sixty participants, ensuring gender balance from both study villages. Given the small population size in both villages as well as inconsistencies in their availability because they live in multiple residences, small sample numbers were considered adequate for the purpose of this study. Secondary data were obtained from relevant books, online journal articles, research papers and were useful in complementing the primary findings, providing context about the Khumbu, Sherpa population and research settings. The purpose of household survey was primarily to gather quantitative data through survey questionnaires from young (20- 30 years), adult (31- 45 years), and elderly (46 years and over) Sherpa members of each village to capture understanding of a range of perceptual and experiential differences among the people of these diverse age groups but about the same issues. The survey questions were broadly categorized into two sections: the first focused on socio-demographic and livelihood issues, while topics related to tourism, community development, environmental changes, and socio-ecological resilience were incorporated in the second section. Besides a few open-ended questions, the survey questions were mostly categorical, including dichotomous (yes/no/don't know), multiple choice, check box as well as interval/ratio and Likert scales.

The survey data were transcribed into English and thematically coded using the Sustainable Livelihood Framework (SLF), which encompasses five livelihood capitals: human, social, natural, physical, and financial. Microsoft Excel was used to facilitate coding process and support systematic analysis of the data. Descriptive statistics were used to summarize the characteristics of households, while thematic analysis analyzed the impacts of tourism on adaptive capacities in each of the villages. Study participants were fully informed of the voluntary nature of the study and their right to withdraw at any time. Informed consent was obtained from all participants by signed or stamped thumbprint forms, a common legal practice in Nepal. Confidentiality and ethical use of the data were respected, and the collected

data was designated solely for the researcher's doctoral thesis and academic work. Fieldwork was conducted during the autumn season employing purposive sampling and snowball technique in close consultations with the key informants and SNP officials.

Results and discussion

Human capital

In the context of Khumbu Sherpa households, four indicators were examined to represent the status of human capital in both study villages including age, education, employment skills, and health condition.

Age

In this study, the working-age population is defined as individuals aged between 20 and 64 years. This classification indicates that a considerable majority of participants—86.66% from Namche and 90% from Thulo Gumela—are situated within this productive age range. Consequently, age emerges as a critical demographic factor that profoundly affects the nature and efficacy of household livelihood strategies and developmental pathways (Gebru & Beyene, 2012).

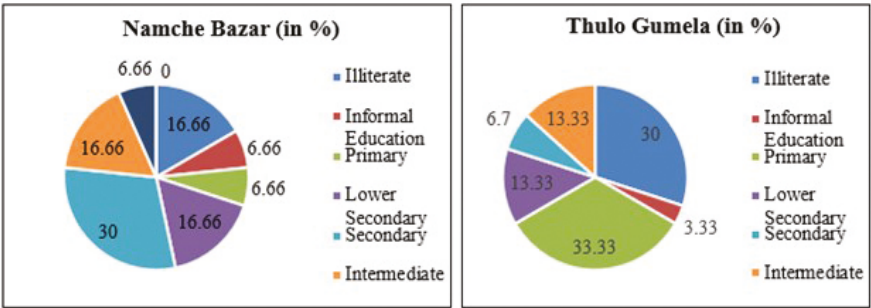
The results suggest that a significant segment of the population has the potential to generate livelihoods in both villages examined. Additionally, out-migration for educational or employment purposes may have led to a reduction in the number of active household members, which in turn impacts the households' overall ability to maintain their livelihoods.

Education

The education-related inquiries in this study were designed to assess the literacy status of respondents, categorizing them as either literate or illiterate. The source of education was also examined, distinguishing between formal education—obtained through educational institutions—and informal education, which is acquired from family members or community sources without attending school. The findings (Figure 2) indicate that a smaller proportion of participants in Namche (16.66%) were illiterate compared to those in Thulo Gumela (30%). Nonetheless, it is noteworthy that a significant majority of participants from both villages were literate. Among the literate respondents, three individuals—two from Namche and one from Thulo Gumela—reported receiving informal education. In terms of educational attainment, 30% of literate participants from Namche and 33.33% from Thulo Gumela completed high school (up to Grade 10) and primary education (up to Grade 5), with these individuals aged between 26 and 35 years. Additionally, similar proportions achieved secondary (up to Grade 8) and intermediate (two years post-Grade 10) levels of education, with figures at 16.66% for Namche and 13.33% for Thulo Gumela. Notably, only two participants from Namche possessed a bachelor's degree, while none held a Master's or Doctorate degree in either village. However, it is plausible that there are additional university or college graduates within these villages but were not captured in this survey, given the small sample size of this study.

Figure 2

Educational attainment of Sherpa households in Namche Bazar and Thulo Gumela



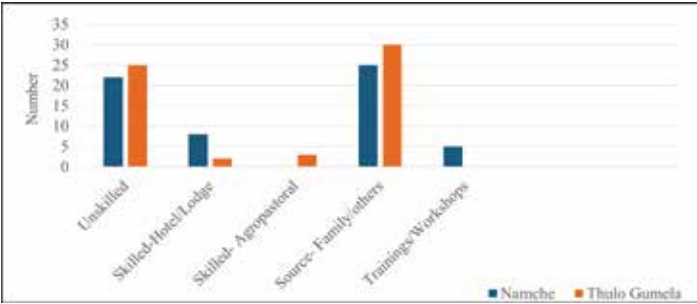
The results indicate that while the literacy rates are promising, there remains room for improvement in higher educational attainment within these communities. Future studies with larger sample sizes could provide more comprehensive insights into the educational landscape and inform strategies to enhance educational access and success for all residents.

Employment skills

The participants in this study were inquired about their employment skills. Those who affirmed having such skills were further questioned regarding the types and sources of these skills. Figure 3 explains a significant proportion of participants from Namche (73.33%) and Thulo Gumela (83.33%) expressed that they did not possess specialized employment skills. However, these individuals believed that the knowledge or skills they utilized for earning a livelihood were primarily acquired through family networks, particularly from elders, as part of the practice of following family occupations. Conversely, among the participants from Namche, 26.66% indicated that they had employment skills, specifically in the hotel and lodge sector. In Thulo Gumela, 16.66% of participants reported their skills in agropastoral activities (10%) and hotel/lodge businesses (6.66%). When discussing the sources of their skills, 75% of skilled participants from Namche and all skilled participants from Thulo Gumela acknowledged that they learned and developed their abilities first through family networks, followed by a practical approach known as ‘learning by doing’, which included knowledge gained from tourists, media outlets, newspapers, and the internet. Additionally, 25% of skilled participants from Namche credited their skill enhancement to training courses and workshops organized by various national and international organizations.

Figure 3

Participants’ employment skills, types and sources



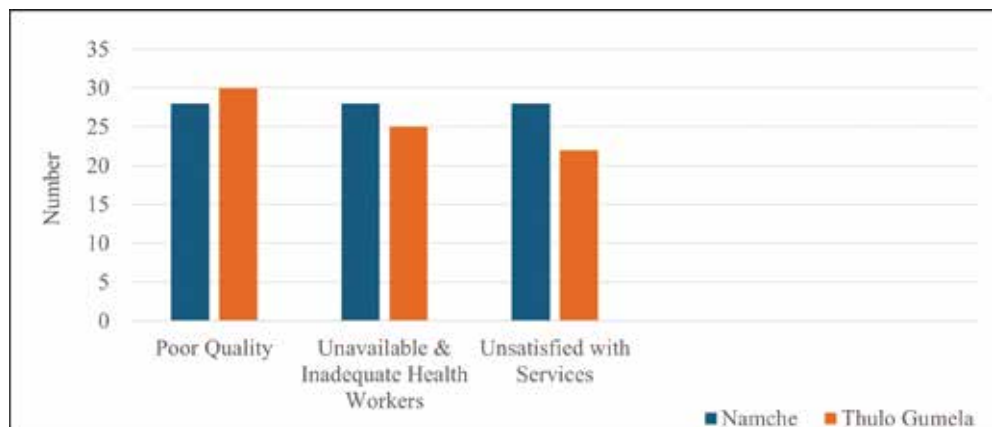
These results demonstrate that the local community based and development organizations including Namche Hotel Association, Namche Women's Group, and Namche Youth Group, Sagarmatha Pollution Control Committee (SPCC), World Wildlife Fund (WWF)-Nepal, EcoHimal-Nepal, the SNP through Buffer Zone programs, CORE International, and USAID have been instrumental in helping the Sherpa people to enhance their skills, awareness and capacity through trainings and workshops in Namche. For example, after attending training sponsored by a Canadian organization-CORE International in 2015, members of the Namche Women Group were successful in obtaining a grant to support their activities such as capacity and leadership building programmes from the local government body (CORE International, 2021). However, these initiatives lack in Thulo Guemla.

Health status

Participants from Namche reported easy access to health services, with the Namche Health Center located at a distance of about a ten-minute gentle walk from the village center. Conversely, those from Thulo Gumela faced significant barriers, having to travel to neighboring villages for healthcare facilities. The closest facility in Jamphute requires a twenty-minute gentle walk, while comprehensive health checkups necessitate a trek of 4 to 6 hours to reach Lukla or Khumjung. Notably, Figure 4 shows that only 6.66% of participants in Namche rated the health services at Namche Health Post as good; conversely, a staggering 93.33% deemed inadequate health services in their local health post at Jamphute based on their past experiences.

Figure 4

The state of health services in Namche and Thulo Gumela



Specific grievances included the inability of health assistants to diagnose conditions accurately or prescribe appropriate medications and a general shortage of healthcare personnel in the village. Furthermore, it was frequently reported that the Namche Health Post was often out of stock of government-supplied generic medicines. All participants from Thulo Gumela expressed concerns regarding the quality of health services available at the Jamphute health post. Specifically, 83.33% of those who sought health services reported frequent unavailability of health assistants and nurses. Furthermore, 88% of the individuals who utilized these services deemed them unsatisfactory, citing that health workers were unable to accurately diagnose their conditions or prescribe appropriate medications. Additionally, concerns were

raised regarding emerging pests and mosquitoes as potential health threats linked to climate change.

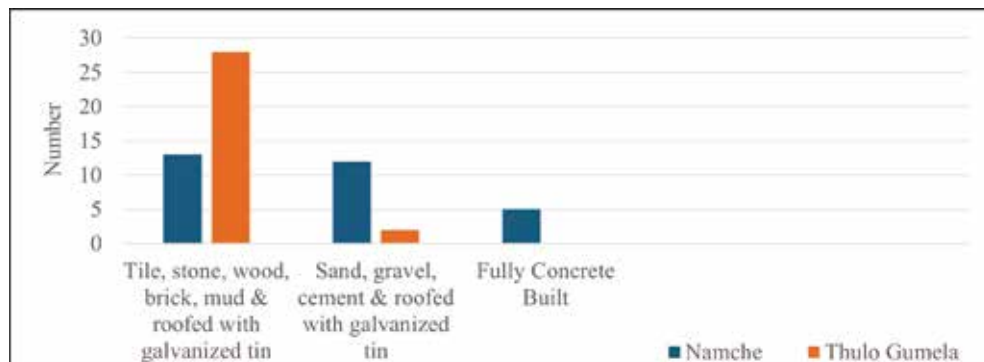
These findings call for urgent action from concerned authorities to invest in enhancing healthcare infrastructure and resources in these villages. By addressing these deficiencies, it is possible to improve health outcomes significantly and ensure that all individuals have access to quality care. Although major cities outside the Khumbu region offer quality hospitals, many households cannot afford treatment due to high costs. The findings also indicate a pressing need for improved medical facilities within closer proximity to these communities, particularly for vulnerable groups such as children under 15 and the elderly over 65.

Physical capital

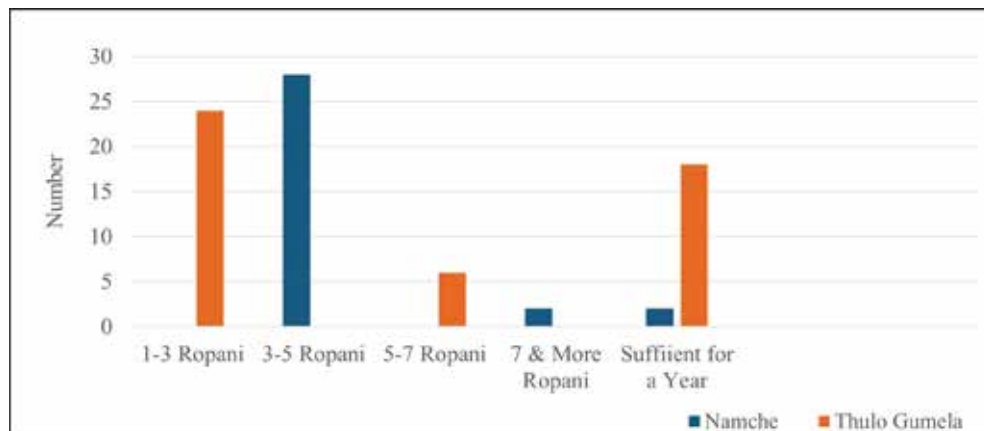
In examining the livelihood systems of Khumbu Sherpa households, several key indicators of physical capital have been identified: (1) housing conditions, (2) land holdings, (3) possessions and valuables, (4) access to technology and equipment, and (5) private services and infrastructures. All participants from both villages acknowledged tourism as the primary driver of their economic prosperity. This underscores the significance of tourism as a vital economic activity that underpins the physical aspects of livelihood capital for these households. To accurately assess the impact of tourism on household economies, it is essential to include all income generated from tourism-related activities in the evaluation. The findings indicate that the state of physical capital is notably stronger in Namche compared to Thulo Gumela. The following three subsections will provide a detailed overview of the status of physical livelihood capital among the households surveyed.

Housing conditions

The architectural design of the newly constructed Sherpa houses in the Khumbu region has undergone significant transformations over the years, particularly following the surge in Everest tourism that began in the 1970s (Nepal, 2002). Participants were surveyed regarding their housing types and construction materials. None resided in traditional thatched-roof homes constructed from wood or stone or mud. Figure 5 demonstrates that in Namche, 43.33% of participants lived in houses made from tile, stone, wood, brick, and/or mud with galvanized tin roofs, while a striking 93.33% of those in Thulo Gumela reported similar constructions. The remaining participants' homes—except for five in Namche—were modern structures built with sand, gravel, and cement and also roofed with galvanized tin. Among these five homes in Namche (16.66%), all were constructed entirely of concrete. This transition suggests that Sherpa households in Khumbu are moving towards using modern materials. Improvements in the built environment have come from two key conditions: reduced access to traditional materials, and increased availability and the desirability for modern resources when building homes. This is a tipping point for households, having greater levels of economic conditions, along with improvements in both economic and physical capital. Even if the use of concrete raises sustainability questions (Watson & King, 2018; Watts, 2019), these have been considered climate resilient and thus suitable for the people of high Himalayas such as Khumbu (Karki, Burton, & Mackey, 2020; Wood et al. 2020). Additionally, traditional materials, known for their climate and earthquake resilience, are becoming less accessible due to extraction restrictions governed by the local and SNP regulations (Adhikary & Johnson, 2025).

Figure 5*Type of house and house building materials in Namche and Thulo Gumela***Land holding**

Landholding is an essential aspect of a household's physical capital in the Sustainable Livelihood Framework, representing the total area of arable and residential land. For agropastoral households, it is crucial as their main livelihood source. In both villages, khet or kharka were not owned by any households, likely due to the rocky terrain and lack of irrigation. All participants owned at least one ropani of land, with Namche households generally holding more land than those in Thulo Gumela. While 93.33% of Namche households owned three to five ropanis, 80% of Thulo Gumela households owned one to three ropanis. Regarding food sufficiency, only 6.66% of Namche participants felt their vegetables were adequate for a year, compared to 60% in Thulo Gumela.

Figure 6*Landholding size of participants' households*

The data shows that while most Namche residents own large plots of land, they do not use them efficiently for agriculture, resulting in inadequate yields to support their households. This inefficiency is partly due to a lack of maintained agricultural skills, leading to an overreliance on tourism as their primary livelihood, which is vulnerable to economic

fluctuations and external challenges like COVID-19 and climate change. Although greenhouses are commonly used for vegetable cultivation in Namche, they are unnecessary in Thulo Gumela due to its favorable climate. Additionally, residents in both villages must purchase essential household items like rice and oil from local shops or markets.

Possessions and valuables

Affluent households in Khumbu are characterized by possessions such as hotels or lodges with modern amenities, attached-bathrooms, solar heating systems, large televisions, and substantial cultivable land. They also have close ties with travel agencies and receive regular remittances from family members. Observation during my fieldwork and the collected data reveals that most surveyed households, except for 13.33% in Thulo Gumela, possessed modern appliances like gas stoves and electric heaters, indicating a standard of a 'modern' home. In Thulo Gumela, 43.33% of households lacked a gas cylinder and stove, unlike those in Namche. Nevertheless, all participants acknowledged these items as standard in Khumbu society, viewing them as essential assets that enhance a household's physical capital.

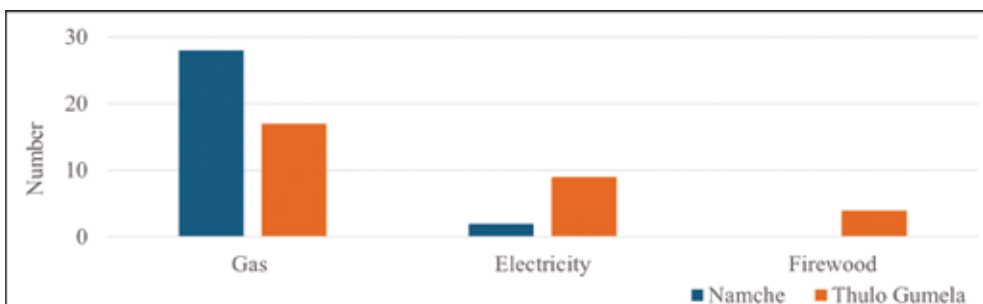
This shows absolute discrepancies in physical capital as a consequence of financial capital, driven by tourism access for the households of these villages. This highlights the need for inclusive development to bridge regional inequalities in livelihood opportunities and infrastructure among on route and off route villages in Khumbu.

Technology/equipment

Evidence from Khumbu illustrates a shift from traditional to modern livelihoods due to the impact of Everest tourism (Nepal, 2015). This modernization has led to significant changes in the lives of Sherpas, driven by their interactions with international tourists. Many Sherpas now utilize modern goods and technologies, such as down jackets and alternative energy sources like LPG, which have been financially supported by tourism income. Over time, advancements such as micro-hydropower, biogas, solar panels, and LPG gained popularity. In this study, 93.33% of Namche participants reported using LPG for cooking, with minimal reliance on electricity (6.66%) and firewood. Only one household in Namche was using solar power for lighting. In Thulo Gumela, 56.66% of households cited LPG as their main cooking energy source and one used solar power for anything.

Figure 7

Main source of energy for cooking



These findings suggest that solar energy has been underutilized in Khumbu. Transitioning to solar power could significantly reduce dependence on firewood for both villages and mitigate

the costs associated with electricity. Given the potential threats posed by climate change to Everest tourism, solar energy emerges as a sustainable alternative that could enhance resilience against these challenges. Although initial installation costs for solar systems are higher than ongoing electricity expenses, they offer long-term savings by decreasing overall energy costs and diminishing reliance on traditional energy sources and environmental impacts.

Public/private infrastructure and services

Participants from both study villages reported equal access to basic services such as electricity, piped water, mobile phones, education, and healthcare; however, service quality and availability were significantly better in Namche. This aligns with previous studies (Fisher, 1990; Sherpa, 2014; Stevens, 1993), which note that only Lukla and Namche have received substantial infrastructure development and external investment. Modern toilets were present in both villages, though 26.66% of Namche and 36.66% of Thulo Gumela households still used traditional composting toilets for their manure-producing benefits. Namche residents also reported receiving technical support from national and international organizations, a resource absent from Thulo Gumela. A shared concern in both villages was the road construction from Surke to Salleri. While expected to reduce travel costs and commodity prices, participants expressed worries about potential environmental degradation, infrastructure strain, and increased tourism pressure.

While both villages have access to basic services, Namche benefits from better quality and external support. To ensure balanced development, authorities should prioritize infrastructure in Thulo Gumela and other off-route villages. The upcoming road project presents economic opportunities but also raises environmental and infrastructure concerns, underscoring the need for equitable, sustainable planning in the Khumbu region.

Natural capital

Prior to the advent of tourism in the Khumbu region, the livelihoods and activities of the Khumbu Sherpa people were primarily centered around the sustainable extraction of natural resources. The evaluation of natural capital at the household level typically considers the availability and accessibility of local resources that families utilize from their natural surroundings to support their livelihood strategies (Bennett & Dearden, 2014; Nguyen et al., 2015). In particular, for Khumbu Sherpa households, key indicators of their natural capital include soil, forests, pastures, and water resources.

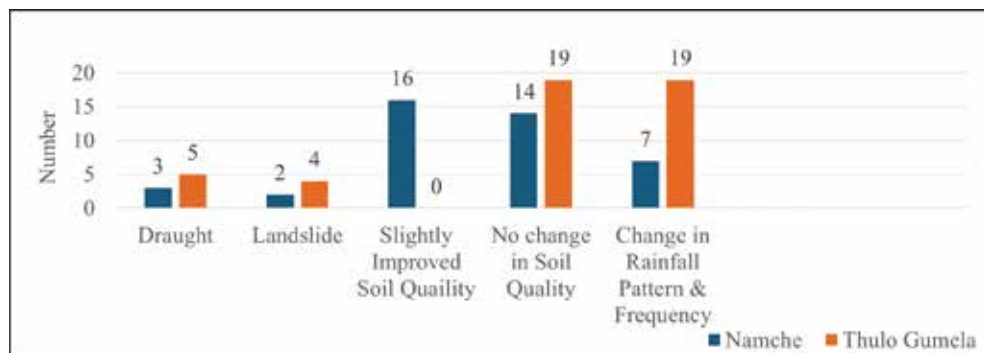
Soil

In a quest for understanding the state of soil quality within the respective study villages, participants were asked about their observations and experiences of drought and landslide; changes in soil fertility; and patterns and frequency of rainfall over the last three to seven years. Namche households are less involved in farming compared to Thulo Gumela. The results as illustrated in Figure 8 demonstrate that only 10% of the participants in Namche and 16.66 % of the participants in Thulo Gumela observed and experienced drought. Correspondingly, 6.66% of the participants in Namche and 13.33% of the participants in Thulo Gumela observed and experienced landslides. In relation to soil quality changes, only 53.33% of participants from Namche reported a slight improvement in conditions. Conversely, 46.67% of Namche participants and 63.33% from Thulo Gumela indicated that there was no change, without offering additional details regarding the soil quality or fertility in their

respective villages, nor whether these conditions had improved or declined. Also, 23.33% of the participants in Namche and 63.33% of the participants in Thulo Gumela observed and experienced changes in the pattern and frequency of rainfall and reported incidents of irregular precipitation, with less rainfall during winter and more rainfall during summer months.

Figure 8

The state of soil quality/fertility and change in the pattern and frequency of rainfall

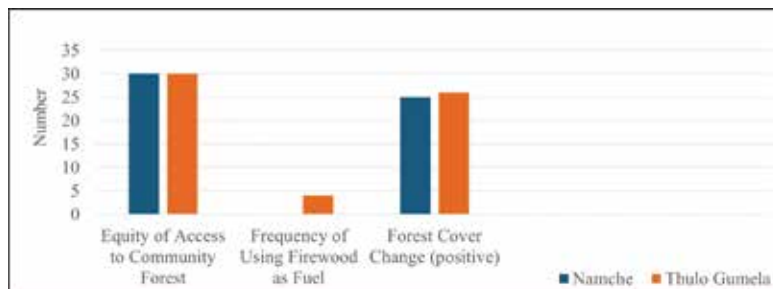


These shifts can have profound implications for agriculture and overall soil fertility, as consistent water supply is critical for crop growth. The combined insights from these results indicate potential long-term effects on the livelihoods of Khumbu residents. Slight improvements in soil quality may not offset the negative effects of changing rainfall, posing risks to food security and agriculture, therefore requiring further research and innovative strategies.

Forests

Forest products remain vital to rural livelihoods in Khumbu, with firewood, timber, and medicinal herbs playing key roles. While the creation of Sagarmatha National Park led to deforestation in Pharak, the Buffer Zone now permits limited, sustainably managed access through community forestry. Participants reported equitable forest access, though fuel usage varied: 13.33% in Thulo Gumela used firewood, while none in Namche did, with LPG preferred in both villages. Gas stoves were seen as essential, and lack of one signified economic hardship. Most Thulo Gumela households using firewood felt community forests met their needs. A majority—83.33% in Namche and 86.66% in Thulo Gumela—observed improved forest density over time.

The findings highlight challenges related to economic accessibility and resource use disparities among different communities; they also point towards successful initiatives that promote sustainable forestry management and foster positive attitudes towards forest conservation.

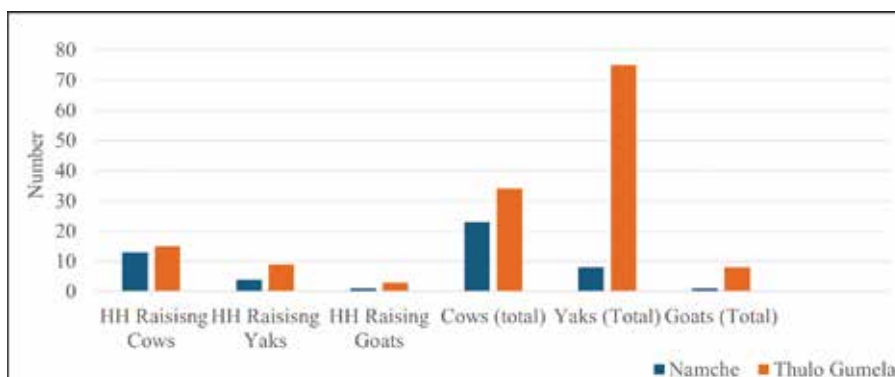
Figure 9*The state of forest and forest use by participants' households*

However, since the costs of a gas cylinder and a gas stove are considerably expensive, households with financial difficulties may be unable to afford these.

Pastures/ grazing lands

Pastures are vital for agropastoral communities as they serve as the main forage for livestock, with their quality affected by grazing frequency and herd size. Surveys revealed that in Namche, 43.33% of households owned 23 cows, while in Thulo Gumela, 50% raised 34 cows. Additionally, yaks were kept by four households in Namche (totaling eight) and nine in Thulo Gumela (totaling 75). Despite a ban on goats by SNP since the early 1980s, some households still raised them; one household in Namche had one goat, and three in Thulo Gumela had eight collectively. Participants reported challenges regarding grazing lands and livestock decline; 66.66% of Namche participants stated insufficient grazing was not a reason for stopping livestock raising, whereas 70% in Thulo Gumela cited inadequate pasture quality as a barrier. Declines were attributed to either lack of grazing land or both lack of land and labor availability: 40% of Namche participants cited the former while 60% indicated both issues; in Thulo Gumela, these figures were 33.33% and 66.66%, respectively.

Namche households benefit from Everest-route tourism and rely less on livestock, while Thulo Gumela faces limited tourism and shrinking pastures, reducing income opportunities. Targeted support in tourism and pasture management is needed to enhance livelihoods and resilience.

Figure 10*Type and number of livestock raised by participants' households*

Water resources

Access to safe drinking water is crucial for health (UNWWAP, 2015). In Khumbu, piped water now serves most villages, replacing reliance on springs, rivers, and wells. Over half of participants from Namche (66.7%) and Thulo Gumela (53.3%) use piped water for backyard irrigation. However, 60% of Namche and 46.7% of Thulo Gumela residents reported occasional supply disruptions caused by natural disasters and infrastructure damage. Human factors like poor waste management also harm water quality. Some Namche households received NGO support for better water management. Despite progress, Khumbu faces ongoing challenges to water quality and supply due to climate change and dependence on glacier melt and rainfall. Sustainable management and external assistance are essential to safeguard long-term water security, especially for agriculture and livestock.

Despite improved water access, Khumbu faces challenges in water quality and supply due to natural and human factors. Dependence on glacier melt and rainfall, combined with climate change, threatens long-term water security, especially for farming and livestock. Sustainable management and external support are essential to address these risks.

Social capital

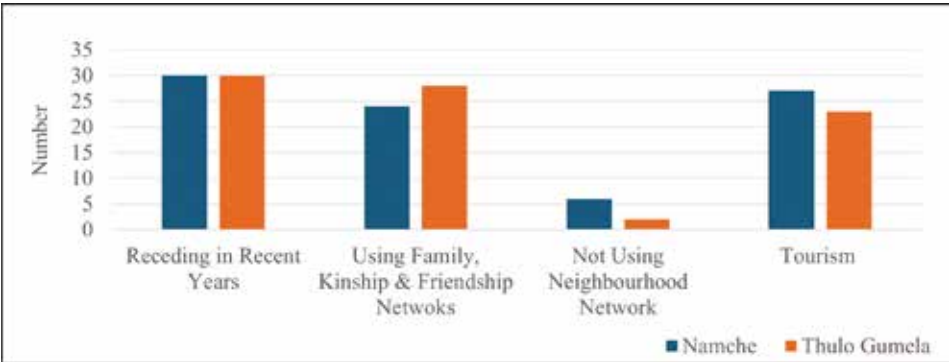
Social capital is one of the five capitals in livelihood systems, enhancing social aspects through trust, norms, rules, values, reciprocity, and networks that promote collective action for mutual benefits (Bhandari & Chang, 2013; Endris et al., 2017). Its forms vary based on community needs and social networking levels. This study focuses on the existence and size of networks among family, friends, kinship, and neighbors, as well as participation in community meetings and gatherings, to assess social solidarity among Khumbu Sherpa households and their potential for livelihood improvement.

Family, friend, kinship and neighborhood networks

In the Khumbu Sherpa community, reciprocity in goods and labor is a significant aspect of social networking (Ortner, 1978; Pandey, 1994; Sherpa, 2014). Surveys showed that traditional exchanges among family, friends, and neighbors have declined, mainly due to tourism’s cash influx—cited by 90% in Namche and 76.7% in Thulo Gumela. While reciprocity was vital for household sustainability in the past, 20% of Namche and 6.7% of Thulo Gumela participants reported no longer relying on neighborhood networks.

Figure 11

Sherpas’ current practice of reciprocity system and causes of its decline



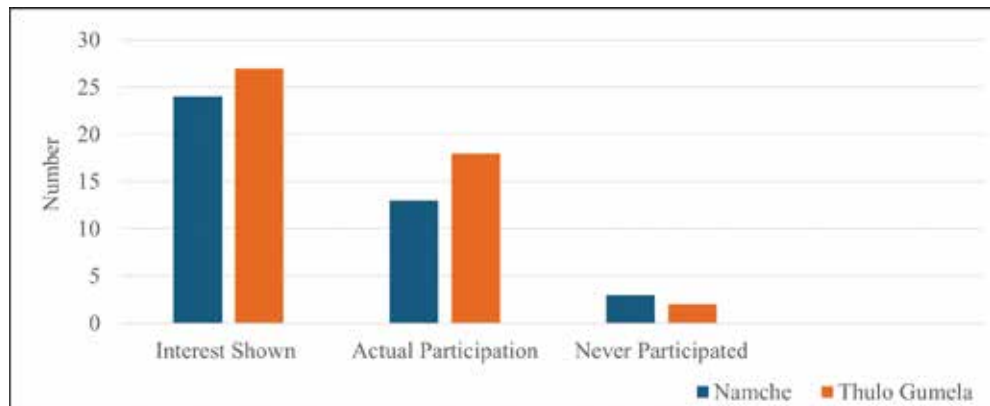
The data indicates a decline in Sherpa households' community-based networks, likely driven by tourism-related financial independence or reduced social obligations. This may challenge traditional cultural practices and affect long-term community cohesion amid ongoing modernization.

Participation in community meetings and social gatherings

The degree of involvement of people in communal and/or social work activities is also a key indicator of social capital and thus indicates the strength of relationships between social institutions and individuals within a community. In Namche, 80% showed interest in community events, with 54.16 % actual participation. Likewise, Thulo Gumela had 90% interest and 60% participation. Awareness of development initiatives was lower in Thulo Gumela (13.33%) than Namche (3.33%). While social gatherings and community meetings still occur, their frequency has declined, with 90% of Namche and 80% of Thulo Gumela participants noting this change. These events typically take place during the summer months (June to September) when tourism is less demanding, and the weather is more favorable.

Figure 12

The state of participation in community meetings and social gatherings



This indicates that there is a strong interest in community engagement within both villages, actual participation remains low. Addressing barriers to participation and revitalizing the frequency of social gatherings may enhance community cohesion and ensure that cultural practices continue to thrive.

Financial capital

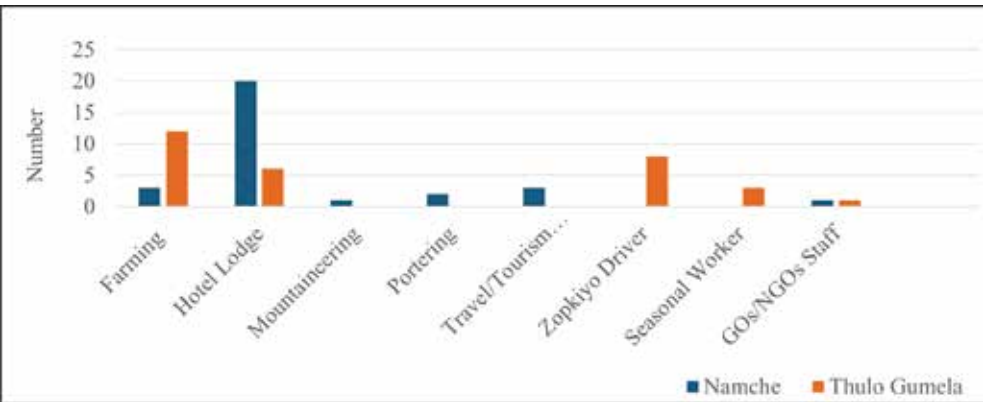
Financial capital provides individuals with access to essential monetary resources for their livelihoods (DFID, 2011; Ding et al., 2018). It is the most adaptable form of livelihood capital due to its ease of conversion into other types. In the context of Khumbu Sherpa livelihoods, financial capital encompasses economic resources including cash income (primary income source), credit (loan sources and purposes), savings (financial institutions for security), and self-perception of financial wellbeing (individual ranking of economic status within the community).

Cash/income

The survey assessed household income by identifying cash earners, types of work, and main income sources. Overall, as illustrated in Figure 13, ninety percent of the participants' households earned money from off-farm activities, while 10% relied on agriculture. Among those engaged in off-farm work, 74.07% were involved in hotel or lodge businesses, with 59.26% as owners and 14.81% as workers. Notably, only one participant (3.7%) was involved in mountaineering, and two (7.4%) in high altitude portering, a stark contrast to past trends where many Sherpas were porters and climbers. Additionally, 11.11% of participants reported income from travel and trekking agencies, while 3.7% derived Participants from the village received cash gifts and donations from family, friends, and foreign tourists. In Namche, 10% reported that they earned cash from agriculture. In Thulo Gumela, 60% relied on non-farm income while 40% depended on farming. Most agricultural households met their food needs and sold surplus locally. Thulo Gumela participants also earned from homestays (6.66%), government services (13.33%), zopkiyo transport (26.64%), seasonal work (10%), and temporary local government roles (3.33%).

Figure 13

Income source of participants' households



These findings underscore the importance of diversifying income sources and fostering community support systems in enhancing resilience among households reliant on tourism. Integrating improved agriculture with tourism and social cohesion can help ensure sustainable and adaptable livelihoods amid economic uncertainty.

Credit/debit

Historically, the Sherpa people of Khumbu relied on informal networks of kinship, friendship, and community for their financial needs, as there were no formal financial institutions. These community-based support systems fostered trust and reciprocity, facilitating socio-cultural activities. With the rise in Everest tourism, modern financial services emerged, leading to the establishment of cooperatives and banks in the region. Namche hosts two commercial banks and a cooperative linked to the Khumbu Mountain Centre project, while Thulo Gumela lacks formal financial institutions. Although participants from both villages reported no major financial issues, Thulo Gumela residents relied more on social networks for borrowing, with 63.33% favoring informal lending over traveling to Lukla or Namche and dealing with

bureaucratic hurdles.

This situation illustrates a critical transition period where informal practices coexist with formal institutions, reflecting broader socio-economic changes within the region.

Savings

Cash-saving practices are vital for managing livelihood risks, but most Khumbu villages lack formal financial institutions due to remoteness and small populations. Only Namche and Lukla offer banking services. As a result, 90% of Namche participants used local banks, while 76.76% in Thulo Gumela stored savings at home. Additionally, 10% in Namche and 23.33% in Thulo Gumela lent money informally to trusted contacts with agreed terms.

This highlights two distinct saving methods within the Khumbu Sherpa community: those with bank access utilize modern financing, while others rely on traditional practices that foster social relations and trust—key elements of their livelihood strategies. While the later system fosters trust and community ties, there may be a chance to expose individuals to risks if borrowers default on their obligations.

Conclusions

The findings of this study provide critical insights into the livelihood systems of Sherpa households in the Khumbu region, particularly highlighting the contrasting economic dynamics between Namche and Thulo Gumela. Utilizing the DFID's Sustainable Livelihood Framework (SLF), this research effectively categorized household resources into human, physical, natural, social, and financial capitals, thereby allowing for a nuanced analysis of how these assets influence livelihoods.

While Namche benefits from strong tourism-based income, its reliance on tourism raises concerns about economic resilience amid external shocks like climate change and pandemics. Thulo Gumela's diversified livelihood strategy appears more stable and sustainable. The study highlights social and economic disparities driven by unequal access to tourism, calling for targeted policies to promote equitable growth. Climate change and recent crises, such as the 2015 earthquake and COVID-19, underscore the need for a comprehensive approach to support sustainable livelihoods in the Khumbu region. To reduce tourism-related risks, authorities should promote economic diversification in Namche and support alternative livelihoods. Equitable distribution of tourism benefits and improved infrastructure in Thulo Gumela are essential for balanced development. Given the threats of climate change and pandemics, tourism policies must prioritize environmental sustainability, climate-resilient infrastructure, and adaptive strategies to protect both livelihoods and ecosystems.

This research advocates for a multi-faceted, participatory policy approach that includes local stakeholder input to ensure responsive and effective interventions. Aligning livelihoods with conservation goals is key to enhancing Sherpa community resilience and supporting the broader objectives of Sagarmatha National Park and its Buffer Zone. Policymakers are urged to adopt sustainable strategies that benefit all Khumbu villages—both along and off the main trekking route—for a resilient and thriving future.

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Table 1

Royalty Fees for Foreign Climbers on Per Person in Different Seasons

Mountains	Spring	Autumn	Winter
Everest normal route	\$11,000	\$5,500	\$2750
Everest another route	\$11,000	\$5,000	\$2,500
Above 8000-meter mountains	\$1,800	\$900	\$450

Note. The amounts are as per the DoT's report of 2021 December.

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In the Discussion section, author should evaluate and interpret the findings in perspective of previous studies and of the working hypotheses. The implications of the research findings should be discussed in the broadest context.

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Chauhan, R. & Thakuri, S. (2017). Periglacial environment in Nepal Himalaya: Present contexts and future prospects. *Nepal Journal of Environmental Science*, 5, 35-40.

Gruber, S. & Haeberli, W. (2007). Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change. *Journal of Geophysical Research*, 112, F02S18. <http://doi.org/10.1029/2006JF000547>

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Knutti, R. (2014). *IPCC working group I AR5 snapshot: The rcp85 experiment* [Data set]. DKRZ World Data Center for Climate. <https://doi.org/10.1594/WDCC/ETHR8>.

Internal publications, conference proceedings, etc.; include sufficient information for the reader to locate the reference. In particular references to conferences should contain the address of the organization responsible.

Author is suggested to format citation and references in the standard APA 7th edition.

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