

Mapping exposure to snow in a developing African context: implications for human and livestock vulnerability in Lesotho

S. W. Grab · J. H. Linde

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Abstract Alpine cryospheric hazards are becoming increasingly prominent under current global/regional climate change scenarios and receiving wide scientific coverage from, in particular, northern hemisphere mountain regions associated with glaciers, permafrost, and extensive seasonal snow cover. However, there is a general paucity of knowledge and attention on cryospheric hazards associated with mountain environments only occasionally/rarely impacted by heavy seasonal snowfalls or severe frost events, particularly those in developing and southern hemisphere regions. Prolonged snow cover in the Lesotho Highlands sometimes carries the consequence of human and livestock deaths owing to isolation and exposure in this developing region. We use daily Moderate Resolution Imaging Spectroradiometer snow cover images for the period 2003–2010, to establish the frequency, extent, and timing of snowfalls across Lesotho. In addition, a digital shape file containing the location, name, and district attributes of 2,016 villages across Lesotho was used to assist in the construction of a village exposure to snow index. A ranking system was applied to each village according to the seasonal duration of snow cover, and the accessibility and proximity to the nearest road. Snowfalls occur on average between 1 and 8 times per annum, with village exposure to snow (*potential* vulnerability) being generally low, particularly for the lowlands and Senqu River Valley. However, the study identifies that some high-altitude (>2,500 m) villages such as Thoteng, Letseng-la-Terae, and Mabalane are, on occasion, highly exposed to prolonged snow cover, and particularly so during the mid-snow season of July/August. We demonstrate the importance of applying spatiotemporal assessments on infrequent snow occurrences (which carry associated hazards) in developing mountain regions such as Lesotho, with implications to reduce livelihood risks through improved disaster preparedness and a well-informed, focused emergency response.

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1 Introduction

Snowfalls are often associated with the onset of cold conditions and can pose substantial threats to people, livestock, and infrastructure (Kääb 2002; Prior and Kendon 2011), most particularly in developing regions where preparedness for such events is inadequate. In addition, flooding associated with rapid snowmelt poses a threat to low-lying regions and communities (Oesch et al. 2002; Haq 2008). The ‘snow hazard’ is still widely defined as ‘comprising all the perils that snow and ice present, both in themselves and in association with other weather conditions’ (Rooney 1967, p. 538). Given that this definition does not acknowledge the associated role of geophysical phenomena (e.g., substrate and slope dynamics, earthquakes, volcanic eruptions) in the development of a ‘snow hazard,’ we propose that the ‘snow hazard’ can be redefined as ‘comprising all the perils that snow and ice present, directly, both in themselves and in association with other earth and atmospheric phenomena, and indirectly through snow melt and/or [re-]freeze.’

In southern Africa, the Kingdom of Lesotho receives winter snowfalls with seasonal snow cover lasting several weeks during some years, and although these occasionally result in human and livestock fatalities (Mulder and Grab 2002, 2009; Grab and Nash 2010), no previous scientific publications have explored snow [and associated severe cold] as a *potential* hazard in the subcontinent, possibly given that such occasions are overshadowed by more frequent and widespread drought, flood, and storm (lightning, tornados, and other catastrophic wind events) hazards (see for example: Leichenko and O’Brien 2002; Du Plessis 2002; Msangi 2004; Goliger and Retief 2007; Stringer et al. 2009). Our aim is to establish the spatiotemporal exposure to snow [and associated severe cold] for all villages/settlements across Lesotho, and in so doing, also to identify *potential* spatiotemporal snow-related hazards and human vulnerability. To this end, we investigate the duration and extent of seasonal snow cover across Lesotho using multi-temporal Moderate Resolution Imaging Spectroradiometer (MODIS) imagery. Seasonal trends in snow cover are explored using daily MODIS satellite images for an 8-year period (2003–2010). The exposure to snow for 2,016 villages across Lesotho is assessed, based on the duration of snow cover, and expressed according to the incidence of early, mid-, or late season snowfalls. It is hoped that such an approach may assist in identifying the most vulnerable communities during future snowfall events and thus improve the efficiency or spatial focus of evacuation or relief efforts in this underdeveloped region.

2 Snow as a natural hazard

Snow hazards are perhaps best known and documented through the media from northern hemisphere urban regions where snowstorms regularly cause infrastructural damage, power outages, and, in particular, telecommunication and transport disruptions (c.f. Pinto et al. 2007). However, many inhabited mountain regions are arguably most susceptible to snow-related hazards, particularly given the added and/or affiliated risks of earthquakes, volcanic eruptions, avalanches, surficial debris movements (e.g., Lahars), regolith slope failures (e.g., landslides), and flooding (see also Gardner and Dekens 2007). Snow-related

hazards are regularly described for the European Alps where avalanches and consequent fatalities and infrastructural damage are a frequent occurrence (Lehning et al. 1999; Margreth and Funk 1999; Gruber and Bartelt 2007). In parts of Asia, particularly the Himalayan region, the magnitude of avalanche disasters is rapidly increasing as settlements expand into hazard zones (Sharma and Ganju 2000; Gardner and Saczuk 2004; Nadim et al. 2006). To this end, exploitation of land for habitation and agricultural purposes is taking place within known avalanche tracks and consequently has led to fatalities and damage to infrastructure (Richardson and Reynolds 2000; Oberoi and Thakur 2005). For instance, heavy snow in the western mountains of Afghanistan, from December 2007 to January 2008, destroyed dwellings and caused widespread road closures, large livestock losses, and at least 11 fatalities associated with ‘snow slides’ (IFRC 2008). The situation in this case was exacerbated owing to extreme poverty and politically displaced communities. The southern South American Andes and Patagonia are regularly impacted by polar air outbreaks which are accompanied by substantial snowfalls and freezing conditions (Pezza and Ambrizzi 2005). Snow in some high-altitude regions (e.g., Puna communities) is considered the most severe hazard, such that during heavy snow years, families may lose up to 50 % of their Llama (*Lama glama*) and alpaca (*Lama pacos*) livestock (Kuznar 2001). The added impact of volcanic activity occasionally causes rapid snow melt and associated earth slides and lahars, with consequent human/livestock fatalities and hydro-technical hazards along the trans-Andean pipelines (Porter and Savigny 2002; Stern 2004).

Snow hazards in Africa are scarcely documented in the scientific literature, yet countries such as Morocco, Algeria, Tunisia, Libya, South Africa, and Lesotho do, on occasion, experience hazardous snow events. For instance, consequences of the heavy February 2012 snow in Algeria included over 40 deaths, many of them through numerous road accidents, gas, and food shortages, trapped villagers who had to be rescued by the military, and major rail and airline disruptions/cancellations. Given the relatively rare occurrence of such events in parts of north and southern Africa, there is generally poor preparedness and inadequate early warning, thus further reinforcing vulnerability to the snow hazard in parts of these regions. Snow has been identified as a primary hazard in the mountains of Morocco, but the severity of the hazard is variable according to available local technologies and adaptive strategies, such as deferred use of leaf fodder in the event of heavy snowfalls (Bencherifa and Johnson 1991; Auclair et al. 2011).

3 Regional and environmental setting

The landlocked country of Lesotho is situated between longitudes 27°00'E and 29°30'E and latitudes 28°30'S and 30°40'S. The country covers 30,355 km² and consists of four main physiographic zones: the western lowlands, the foothills, Senqu River Valley, and the central and eastern highlands (Schmitz and Rooyani 1987). The highlands account for 80 % of the total land area of Lesotho and contain the highest mountains in southern Africa, ranging from 1,400 to 3,482 m a.s.l at Thabana Ntlenyana (29°30'S, 29°30'E) (Grab et al. 2009). The Maluti Mountains form a distinct range and separate the north-western highlands from the lowlands. The Central and Thaba Putsoa Ranges occupy the interior of Lesotho (Fig. 1). The Drakensberg forms part of the great escarpment and flanks the entire eastern side of Lesotho between latitudes 28°30'S–30°30'S.

Lesotho's climate is influenced both by its latitudinal position in southern Africa and contrasting subregional topographical and altitudinal settings. The Lesotho highlands are

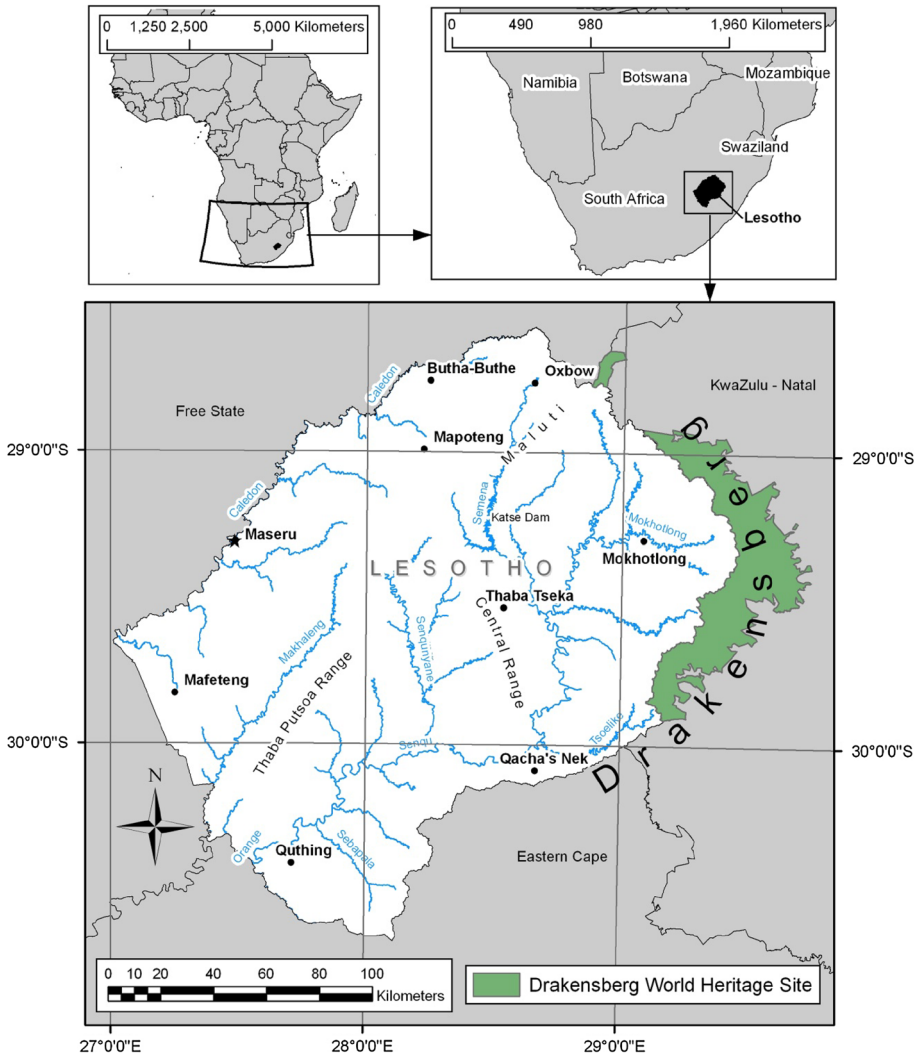


Fig. 1 Lesotho and its location in southern Africa

cool/wet in summer (November–March) and cold/dry in winter (May–September), with 70 % of annual precipitation (~ 600 – $1,000$ mm) falling between November and March (Tyson et al. 1976). Less than 10 % of annual precipitation occurs during the cold season (May–September), yet most of this falls as snow. Snowfalls are usually associated with frontal perturbations in the westerlies. Although an average of eight annual snowfalls are reported for higher altitudes ($>2,500$ m a.s.l.) (Tyson et al. 1976), only one snowfall occurs every 2–3 years in the lowlands ($1,400$ – $1,700$ m a.s.l.) (Grab and Nash 2010). Individual snowfalls are usually <5 cm, but falls of as much as 120 cm have been recorded during historical times (e.g., 1843; see Grab and Nash 2010). Mean seasonal temperatures in the mountains range from ~ 10 °C (December–February) to ~ 0 °C (June–August); ground frost occurs on ~ 180 days/year (Grab 2005). Mean monthly wind speeds recorded in the Sani

Valley (in 2001) vary from 3.39 m s^{-1} (March) to 8.09 m s^{-1} (August); wind gusts of up to $\sim 37 \text{ m s}^{-1}$ have also been measured (Grab 2010).

Lesotho is under considerable pressure for subsistence agricultural land by its growing population of 2.2 million people, who require tenure and a means to establish sustainable livelihoods (Obioha 2010). The country has increasingly high rates of HIV/AIDS prevalence, which compounds the socioeconomic challenges already facing the predominantly impoverished society. Further, considerable climate and rainfall variability have decreased the ability of subsistence farmers to maintain food security and has increased Lesotho's reliance on food imports from South Africa (Ziervogel et al. 2006). It is evident that the country is vulnerable to a myriad of biophysical and socioeconomic hazards, including those associated with snowfalls. The previous transhumance system has become increasingly disrupted during recent years (c.f. Grab and Nüsser 2001) owing to greater demands on grazing land and pasture degradation at lower altitudes; thus, many livestock herds nowadays spend the winter months at high-altitude ['summer'] pastures, thereby placing them at greater risk to snow and cold. However, there is a lack of quantitative information on the frequency and seasonal variability of snowfall and snow duration across Lesotho. More importantly, there has been no previous attempt to establish the spatial variability and extent of snow in the context of a *potential* hazard, impacting Lesotho villages/settlements.

Historical and contemporary accounts of severe snow in Lesotho have recorded human deaths, heavy livestock losses, and damage to fruit trees and crops (see Grab and Nash 2010; Table 1). Given that most villages across the Lesotho highlands are impoverished with inadequate winter clothing and footwear, do not have access to electricity, have a high dependence on local subsistence energy sources (primarily dung and plant matter), practice subsistence agriculture, have poor access to food markets, and lack independent modes of motorized transport, they are particularly vulnerable to the impacts of snowfalls and snow cover lasting in excess of two or more days. Heavy snow in Lesotho is known to damage crops and cause the roofs of dwellings to collapse through snow load, and on occasion, snow avalanches cause slope failures. In addition, severe frost regularly destroys vegetable and grain crops and limits access to water in some high-altitude regions. However, no documented reports exist on economic losses associated with snow and frost in Lesotho. Direct consequences of even light snowfalls include associated severe cold conditions and an inability to (a) collect fuel for making/sustaining fires, (b) thaw snow/ice for drinking, (c) collect or receive food due to road closures and bridle/footpaths being impassable, (d) adequately attend to livestock which in many instances are trapped in remote pastures during such events (given the general absence of sheds), and (e) inadequate grazing for livestock—in many instances causing death and sickness. Table 1 summarizes some of the reported consequences of major snowfalls across Lesotho during recent decades. Notably, given the remote setting, many consequences of annual snowfalls do not reach the media. Two reports, in particular, aptly describe consequences associated with snow hazards in Lesotho:

Snowfall of 20–21 July 1988

People of Lesotho are suffering due to an earlier heavy fall [10 July], in places still 2 m deep, and so cannot collect firewood or water. Some are so desperate that they walk barefoot through snow to find such items, eating snow to survive..... Beeld [Newspaper] (21 July 1988)

More than 50,000 people in mountainous areas of Lesotho were cut off from the outside world and the South African government was requested to assist with air transport of emergency supplies to assist communities. Caelum (1991, p. 115)

Table 1 Documented consequences of snowfall events in Lesotho: 1980–2012

Year	Date	Consequence	Source
1982	Jun 8	Roads closed [for several weeks in places]	The Citizen (Newspaper)
1987	Sep 28	At least 14 human lives claimed Estimated 40,000 sheep and goats died Avalanches destroyed roads Some roads closed for 3 weeks Buildings collapsed Major air rescue operation required	Clark (2001) and Oosterlig (Newspaper)
1988	Jul 21	At least 15 human lives claimed 50,000 people ‘cut off’ from outside world Major air rescue operation required	Beeld (Newspaper) Caelum (1991)
1990	Jul 13	Estimated 200 sheep/lambs died	Die Volksblad (Newspaper)
1990	Sep 19	Major air rescue operation required	Die Volksblad (Newspaper)
1994	Jun 28	Roads closed [for several weeks in places]	Die Volksblad (Newspaper)
1994	Jul 27	Heavy stock and crop losses Telephone and electricity lines down in many places	The Star (Newspaper)
1996	Jun 16	Countless human lives claimed Thousands of angora goats died	Daily News (Newspaper)
1996	Jul 9	Human fatalities [an unknown number] 83 individuals rescued by helicopter ‘Huge stock losses’—Thousands of Angora goats died Power lines destroyed	Beeld (Newspaper)
2001	Jul 23	Many roads across Lesotho closed for several days Villages ‘cutoff’ from the outside world for several days	Beeld (Newspaper)
2002	Jul 16	Southern Lesotho proclaimed a disaster area due to snow Livestock losses	South African Weather Services
2004	Sep 8	15 Tourists trapped in Lesotho snow	This Day (Newspaper)
2005	Sep 6	Tourists trapped in Lesotho snow	Sani Chalet visitors book
2011	Jun 8	Roads closed for several days Tourists trapped in Lesotho snow	Personal communication with Afriski Resort
2012	August	Roads closed for several days in places Tourists trapped in Lesotho snow	Personal communication with Afriski Resort

4 Methodology

4.1 Topographical, road, and village data

Several digital 1:50,000 topographical maps showing segments of South Africa and Lesotho were used to georeference a scanned 1:250,000 topographical map of Lesotho. Ten GCPs were identified on four 1:50,000 digital maps, yielding a total of 40 shared

points of known spatial location with which to reference the 1:250,000 map. The process of updating the spatial reference system for the larger map was accomplished using the ArcGIS *Georeferencing* tool, which produced a fully referenced 1:250,000 digital topographical map of Lesotho with an average root-mean-square (RMS) error of 0.013. A digital shape file containing major and secondary roads as well as the location, name, and district attributes of 2,016 villages was obtained from the Geography Department at the National University of Lesotho. The data were incorporated into the topographical map.

Duration of snow cover on roads was included as an additional indicator of snow exposure. Major roads have tarred or graded surfaces, and secondary roads are untarred, ungraded routes. Due to the varying nature of these surfaces, snow cover is assumed to affect each one differently. Secondary roads are typically more susceptible to snow closures than major roads, or may be blocked by snow for longer periods than major roads which are sometimes cleared of snow. In addition, major roads provide quicker and safer access to stricken areas for emergency vehicles. The ArcGIS Spatial Analyst *Distance* tool was used to construct a raster image with pixel values representing the Euclidean distance from the road vectors for both major and secondary roads. By overlaying the point data from the village database, the Spatial Analyst *Extract Values to Points* tool was used to append the attribute table to include these distance values from major and secondary roads, respectively, for each village. Subsequently, an attribute of snow cover duration was created at each node of the digital road layer. The road network is constantly changing; thus taking the network density and structure into consideration would be difficult, yet possibly deserves a separate follow-up investigation to the current work.

4.2 Moderate Resolution Imaging Spectroradiometer (MODIS) data

Rapid Response imagery has diverse applications in land cover mapping given its near-real time acquisition and is thus increasingly used in the analysis of seasonal snow cover trends (e.g., Haq 2008; Joyce et al. 2009). The MODIS instrument can distinguish snow independent of cloud cover and complex topography, providing superior snow cover area (SCA) estimations over those from other operational platforms such as the Advanced Very High Resolution Radiometer (AVHRR) and Geostationary Operational Environmental Satellite (GOES) systems (Hall et al. 2001; Maurer et al. 2003). The MODIS snow product classification is based on the Normalized Difference Snow Index (NDSI) (Riggs et al. 2006), which distinguishes between snow and clouds or other non-snow surfaces due to the high reflectance of snow in visible wavelengths and low reflectance in the shortwave infrared wavelengths (Klein et al. 1998; Salomonson and Appel 2004). MODIS snow cover mapping is facilitated by means of the SNOMAP threshold (Hall et al. 1995).

Geometrically corrected MODIS images and data products from the Terra and Aqua satellites are from the Rapid Response Web site which provides daily coverage since August 2003. Available data products include several composites of MODIS bands: 1-4-3 (true color), 7-2-1, and 3-6-7. Combinations of bands 7-2-1 and 3-6-7 are valuable for distinguishing snow and ice, as they are highly absorbent in MODIS bands 6 and 7 and very reflective in the visible part of the electromagnetic spectrum. However, daily Aqua or Terra images in the FAS_1 South Africa subset are often subjected to distortion or excessive cloud cover and are thus not suitable for snow mapping. Under these circumstances, the daily image from the corresponding satellite provides a clearer view of the Earth's surface, as the extent of cloud cover can change significantly within the 3-h interval between satellite overpasses (Hall and Riggs 2007). This allows for more consistent temporal coverage of the study region by including satellite images for snowfall events that

would otherwise be excluded from analysis. MODIS Rapid Response imagery was selected on the basis of its 250-m spatial resolution, as opposed to the coarser 500-m resolution MODIS Daily Snow Product imagery.

4.3 MODIS snow classification

IDRISI Kilimanjaro GIS was used to initiate batch-processing modules that facilitated efficient classification and storage of the MODIS dataset. All images were fitted with Universal Transverse Mercator (UTM) Complex-Zone 35S projection. Band 7 and band 4 were extracted from the 1-4-3 and 7-2-1 composite images for the purpose of calculating NDSI and for fitting the SNOMAP algorithm (Hall et al. 1995). Due to the large number of images, IDRISI Kilimanjaro batch-processing tools were used for assigning reflectance values and fitting NDSI and SNOMAP criteria. Pixels were mapped as snow-covered if the NDSI was ≥ 0.4 . Following the SNOMAP methodology, pixels were mapped as snow-covered if the reflectance of band 4 was $> 11\%$ (as suggested by Hall et al. 1995). Finally, SNOMAP images were smoothed by means of a 3×3 median filter and then spatially clipped to exclude pixels outside Lesotho.

4.4 Snow exposure analysis

The snow exposure of village inhabitants to prolonged snow cover, which may reflect potential vulnerability to snow, is calculated by analyzing the spatial location of villages in relation to seasonal snow cover. The input variables for this snow exposure analysis include the village database, snow cover duration maps, and the database of major and secondary roads. Villages were ranked according to their individual exposure to prolonged snow cover and proximity to transport routes.

The total duration of snow cover derived from MODIS SNOMAP images was calculated using the Cell Statistics module in Spatial Analyst Tools. Snow duration maps were created for early snow (April, May, June), mid-snow (July, August), and late snow seasons (September, October, November). Each output image represents the spatial extent of each recorded snow occurrence, with each pixel value representing the total duration (days) of snow cover represented by SNOMAP images. The Spatial Analyst *Extract Values to Points* was used to append the attribute table of the village layer to include a snow duration value from the summed SNOMAP images. Villages were ranked according to the mean number of consecutive days of snow cover and the maximum number of consecutive days of snow cover for the period 2003–2010 (Table 2).

Road proximity to villages was calculated using the ArcGIS Spatial Analyst *Distance* tool, which appended the attribute table of the village database to include variables for each village based on their distance (km) from the nearest major and secondary road. Subsequently, each village received a single rank according to its distance from the nearest type of road (major or secondary) (Table 3). Further, all villages were ranked according to the mean number of consecutive days of snow cover per annum and the maximum number of consecutive days of snow cover on the nearest road for the period 2003–2010 (Table 4). Villages were also ranked according to the duration of snow cover on the nearest major or secondary road using rank values from 1 to 7, which indicate increasing levels of inaccessibility.

Finally, an overall exposure to snow rank is calculated for each village by adding the rank values assigned for the respective snow exposure indicators. The rankings for each of the 5 exposure indicators (mean consecutive days of snow cover per annum, maximum consecutive days of snow cover, proximity to roads, and mean and maximum consecutive days of snow

Table 2 Mean and maximum number of consecutive days that villages are snow-covered per annum, with corresponding exposure ranking scores

Consecutive days of snow cover		Ranking
Mean	Max	
≤0.5	≤1	1
1	2	2
1.5	3	3
2	4	4
2.5	5	5
3	6	6
3.5	7	7
≥4	≥8	8

Table 3 Proximity of villages to the nearest road, with corresponding exposure rank values

Distance to nearest road (km)	Rank value	
	If major road	If secondary road
0–4.25	1	2
4.26–8.5	2	3
8.51–12.75	3	4
12.76–17	4	5
17.01–21.25	5	6
21.26–25.5	6	7
25.51–29.75	7	8
29.76–34	8	9

Table 4 Mean and maximum number of consecutive days that the nearest road to a village is snow cover, with corresponding exposure ranking scores

No of consecutive days with snow cover on the nearest road		Rank value
Mean	Max	
≤0.5	1	1
1	2	2
1.5	3	3
2	4	4
2.5	5	5
3	6	6
3.5	7	7
≥4	8	8

cover on roads) are expressed on a scale of 0–8; thus, the overall potential exposure to snow for each village, expressed as the sum of these rankings, is on a scale of 0–40. While it is acknowledged that snow depth would be a valuable parameter to measure, this is practically not possible. Summaries of the exposure ranking frequency were created for each of the 10 provinces of Lesotho. Finally, the spatial location of each village was linked to its associated exposure index using ArcGIS software, with villages depicted by graduated colors that symbolize their particular exposure (i.e., *potential vulnerability*) to prolonged snow cover.

5 Results

5.1 Snowfall frequency

The monthly frequency of snowfalls in Lesotho (2003–2010) reveals a high inter-annual variability ($SD = 2.56$) in the number and timing of snowfalls (Fig. 2). Most snowfalls (19; 44 %) occurred during the mid-season months of July and August, with June recording an average of 1.38 snowfalls per annum (26 % of annual snowfalls) (Table 5). A total of 17 early season (40 % of annual snowfalls) and 7 late season snowfalls (16 % of annual snowfalls) were recorded. The mid-season period has the highest absolute maximum number of snowfalls per annum (5), as well as the highest mean number of snowfalls per annum (2.38). Late-season snowfalls have the lowest absolute maximum number of snowfalls per annum (2), and the lowest mean number of snowfalls per annum (0.88).

5.2 Extent of snow cover

The highest and lowest cumulative extent of annual snowfalls was measured in 2004 (25,788.95 km²) and 2005 (1,065.78 km²), respectively (Table 6). The most widespread and limited snowfalls were recorded in August 2006 (15,564.20 km²) and June 2004 (82.91 km²), respectively.

5.3 Duration of snow cover

The mean duration of snow-covered area (SCA) following a snowfall is highest during July (11 days), followed by June (9.8 days) and August (9.7 days) (Fig. 3). The duration of snow cover following snowfalls is progressively lower during the months of May (7.4 days), September (5.2 days), April (2 days), and October/November (1 day). This trend is due to the accelerating snowmelt rates associated with considerably warmer spring conditions and is lower during the early season period, suggesting better snow preservation during autumn (April/May) than spring (September/October).

SNOMAP summaries for early season snowfalls indicate that the majority of snow cover on mountain ranges has a mean duration of less than 5 days per annum (Fig. 4). Longest early season snow cover (avg 11–15 days per annum) occurs in isolated patches in the southern Drakensberg. However, the western lowlands and Senqu River Valley remain relatively snow-free throughout the early season period. Mid-season snow cover (avg 1–5 days per annum) is widespread (9,923 km²) on all mountain ranges in Lesotho, especially along the escarpment and the Maluti Range (Fig. 5). Longer lasting snow cover (avg 6–10 days per annum) is prevalent to a lesser extent (2,091 km²), yet occurs extensively along the escarpment near Mokhotlong and Sehlabathebe, as well as in the southern Drakensberg near Quthing. The longest mid-season snow cover (avg 21–25 days per annum) is restricted in extent (6.7 km²) to the southern Drakensberg. The majority of late-season snow cover is concentrated along the escarpment between Mokhotlong and Sehlabathebe where it persists for an average of 1–5 days per annum (Fig. 6).

5.4 Snow cover on roads adjacent to Lesotho villages/settlements

A comparison between the number of villages and the proximity to roads indicates that 1,009 villages are located within 4.25 km of a major road and 874 villages within

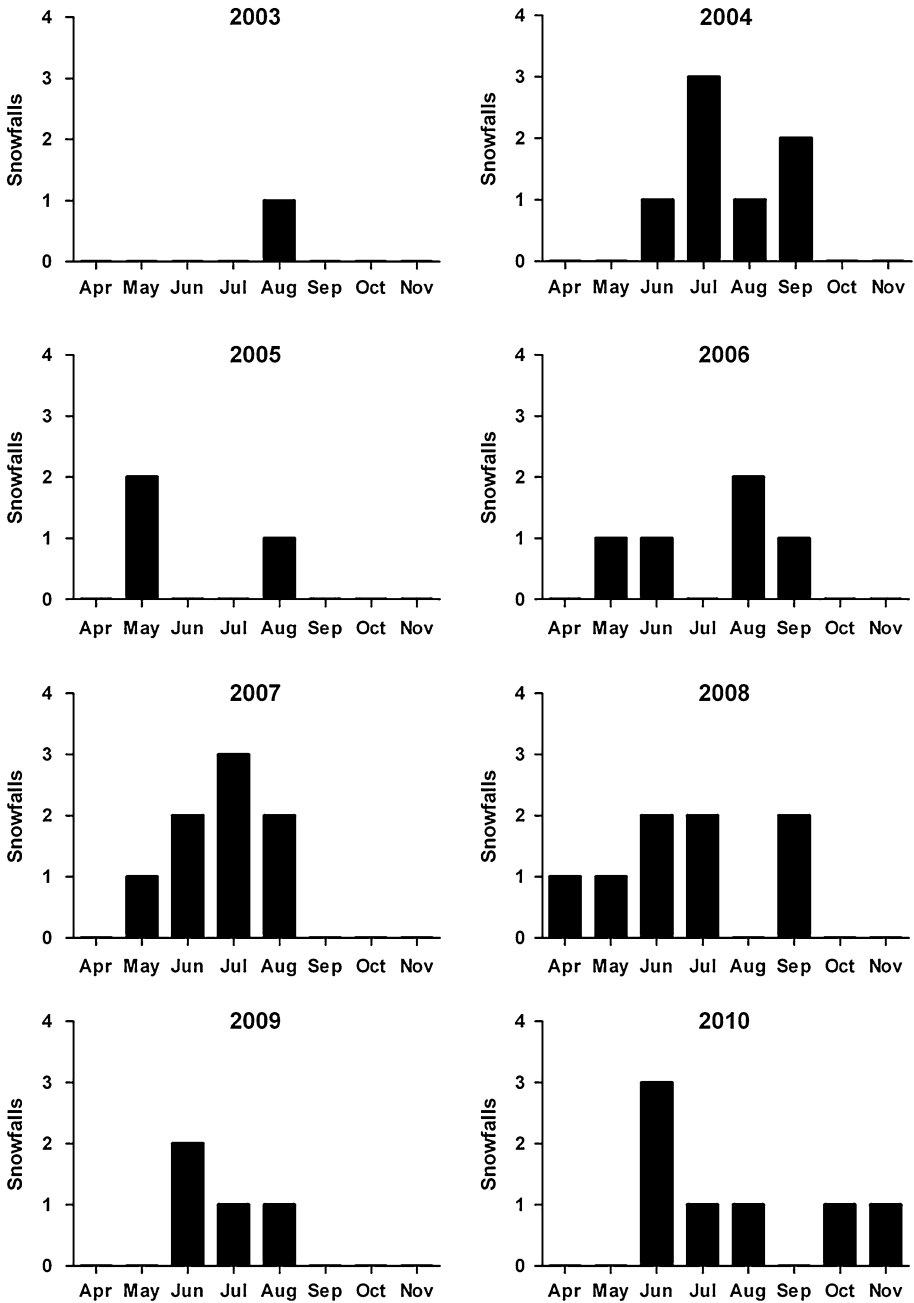


Fig. 2 MODIS-based monthly snowfall frequency over Lesotho for the period 2003–2010 (snowfall statistics: mean = 5.38 pa; median = 6 pa; SD = 2.56 pa; minimum = 1 pa; maximum = 8 pa; $n = 43$)

4.25 km of a secondary road (Table 7). A total of 166 villages are located 12.75–17 km from the nearest major road, and 26 villages are 25.5–29.75 km from the nearest major road.

Table 5 Statistical summary of monthly snowfall frequency per annum for the period 2003–2010, based on MODIS imagery

	Snowfall frequency							
	Early snow season		Mid-snow season			Late snow season		
	April	May	June	July	Aug	Sept	Oct	Nov
Mean (per annum)	0.13	0.63	1.38	1.25	1.13	0.63	0.13	0.13
Median	0	0.5	1.5	1	1	0	0	0
SD	0.35	0.74	1.06	1.28	0.64	0.92	0.35	0.35
Max	1	2	3	3	2	2	1	1
Min	0	0	0	0	0	0	0	0
Total snowfalls	1	5	11	10	9	5	1	1

Table 6 Statistical summary of snowfall extent for the period 2003–2010, based on MODIS imagery

Year	Number of snowfalls	Cumulative extent of snowfalls (km ²)	Mean extent per snowfall (km ²)	Max snowfall extent (km ²)	Min snowfall extent (km ²)	SD
2003	1	5,414.11	5,414.11	–	–	–
2004	7	25,788.95	3,684.14	9,828.24	82.91	4,084.90
2005	3	1,065.78	355.26	500.44	255.06	128.72
2006	5	21,896.73	4,379.35	15,564.20	161.39	6,650.46
2007	8	19,301.02	2,412.63	5,633.11	158.18	2,201.82
2008	8	27,001.67	3,375.21	7,454.98	631.71	2,910.28
2009	4	16,528.38	4,132.10	9,746.14	756.57	4,283.82
2010	7	4,250.00	607.14	1,970.00	175.00	611.78

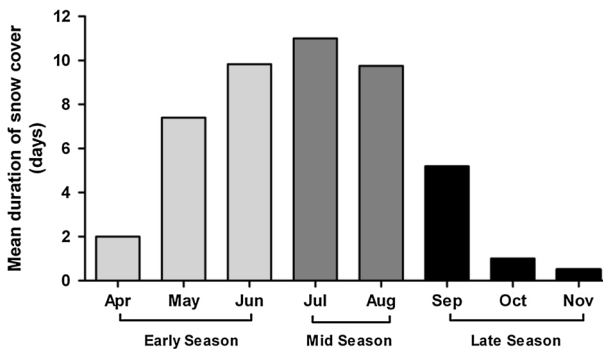


Fig. 3 Mean duration of seasonal snow cover for the period 2003–2010

The majority of villages are situated near roads that experience a short duration of snow cover (Table 8). A total of 2,008 villages have the nearest road snow-covered on average 1 day per annum. Only 8 villages are situated near roads that are on average snow-covered for two or more days per annum, and one village is situated near roads that are on average snow-covered for eight or more days per annum (see Table 8 for further data).

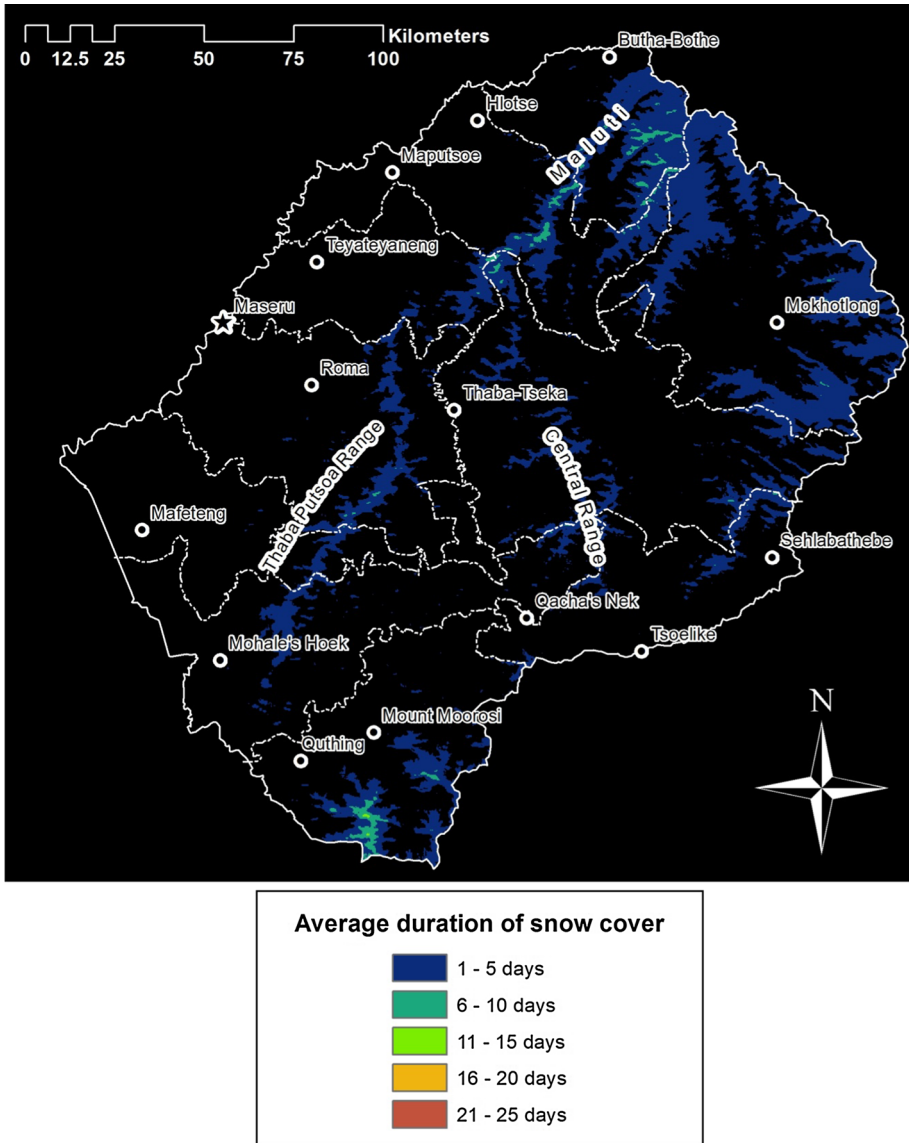


Fig. 4 Mean duration of snow cover per annum for the early snow season (April–June) during the years 2003–2010

5.5 Duration of mean annual snow cover in Lesotho villages/settlements

A comparison between the number of villages and the total duration of snow cover for the years 2003–2010 indicates that 97 % of villages (2,003 villages) are snow-covered for 1 day or less per annum (Table 9). A further 13 villages are snow-covered between 2 and 4 consecutive days per annum, and 12 villages are snow-covered between 4 and 6 consecutive days. A further 33 villages experienced incidences of ≥ 8 consecutive days of snow cover during these years.

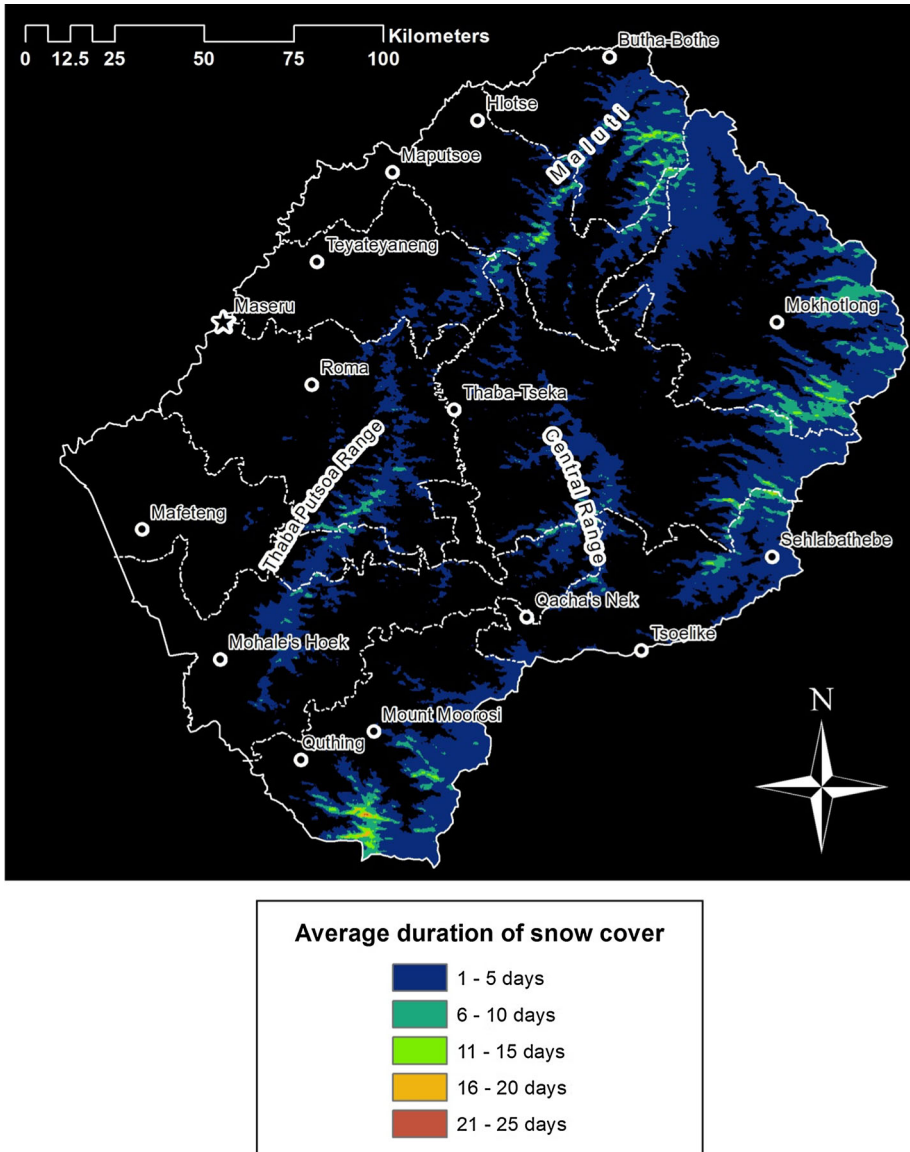


Fig. 5 Mean duration of snow cover per annum for the mid-snow season (July/August) during the years 2003–2010

5.6 Overall exposure to snow

For the period 2003–2010, most settlements in Lesotho were affected by snow during the mid-snow season (1,987 villages; 98.5 % of villages), and marginally fewer were affected during the early (1,974 villages; 97.9 % of villages) and late (1,971 villages; 97.7 % of villages) seasons (Table 10). Based on the exposure to snow ranking system, it is evident that the majority of villages in Lesotho have low snow exposure rankings throughout the cooler seasons. A total of 688 villages (34 % of villages) have a ranking of 1 during the

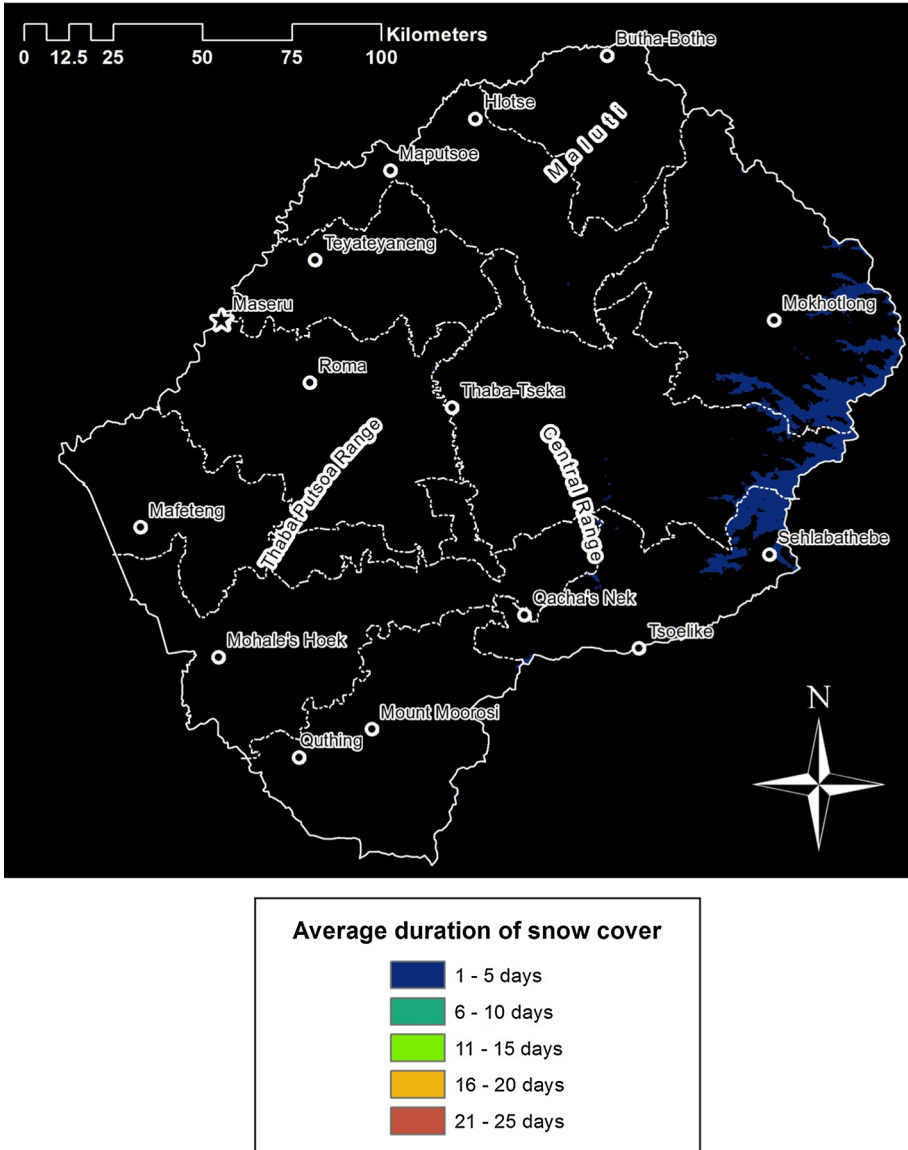


Fig. 6 Mean duration of snow cover per annum for the late snow season (September–November) during the years 2003–2010

early snow season, compared with 458 villages (23 % of villages) during the mid-season and 893 villages (44 % of villages) during the late season. However, 116 villages (6 % of villages) have an exposure ranking of 5 during the early snow season, compared with 141 villages (7 % of villages) during the mid-season (see Fig. 7 for an example) and 104 villages (5 % of villages) during the late season. Five villages (0.3 % of villages) during the early season and 27 villages (1.3 % of villages) during the mid-season have exposure rankings of 10. During the early snow season, only Anone had an exposure ranking of 15. Ha Raninni, Letseng, Liteleng, and Mohlanapeng recorded rankings of 15 during the mid-

Table 7 The proximity of Lesotho villages to the nearest major or secondary road

Distance to nearest road (km)	Number of villages	
	Major roads	Secondary roads
0–4.25	1,009	874
4.26–8.5	458	564
8.51–12.75	227	289
12.76–17	166	138
17.01–21.25	82	88
21.26–25.5	48	48
25.51–29.75	26	15
29.76–34	0	0

Table 8 Mean and maximum consecutive days per annum for which the nearest roads to villages are snow-covered for the period 2003–2010

Consecutive days nearest road is snow-covered		Number of villages
≤1	Mean (per annum)	2,008
	Max	1,846
2	Mean (per annum)	6
	Max	96
3	Mean (per annum)	1
	Max	29
4	Mean (per annum)	0
	Max	5
5	Mean (per annum)	0
	Max	4
6	Mean (per annum)	0
	Max	3
7	Mean (per annum)	0
	Max	0
≥8	Mean (per annum)	1
	Max	33

snow season (Table 11). High mid-season exposure rankings were recorded for Thoteng (18), Letseng-la-Terae (16), and Mabalane (16) (Figs. 7, 8; Table 11). Villages with the highest late season exposure to snow rankings include Liphalleng, Lithipeng, Khotojieng, Likonyeleng, and Ha Mashenephe (each 9).

5.7 Topographical setting of villages/settlements

Most villages in Lesotho are established between altitudes ranging from 1,400 to 2,700 m a.s.l. Only three villages are located above 2,700 m a.s.l.: an unnamed village (Butha-Buthe district) on a north-facing slope between 2700 and 2,800 m a.s.l, Ha Rannini on a west-facing slope between 2,800 and 2,900 m a.s.l, and Letseng-la-Terae on a north-facing slope between 3,000 and 3,100 m a.s.l. West-facing slope aspects generally host fewer villages (347) than north- (831) and

Table 9 Mean and maximum number of consecutive days that villages are snow-covered per annum for the period 2003–2010

Consecutive days of snow cover		Number of villages
≤1	Mean (per annum)	2,003
	Max	1,845
2	Mean (per annum)	10
	Max	97
3	Mean (per annum)	2
	Max	29
4	Mean (per annum)	1
	Max	5
5	Mean (per annum)	0
	Max	4
6	Mean (per annum)	0
	Max	3
7	Mean (per annum)	0
	Max	0
≥8	Mean (per annum)	0
	Max	33

Table 10 Number of villages and their seasonal snow vulnerability ranking for the period 2003–2010

Exposure ranking	Early season	Mid-season	Late season
1	688 (34 %)	458 (23 %)	893 (44 %)
2	378 (19 %)	492 (24 %)	332 (16 %)
3	382 (19 %)	414 (21 %)	274 (14 %)
4	259 (13 %)	270 (13 %)	240 (12 %)
5	116 (6 %)	141 (7 %)	104 (5 %)
6	75 (4 %)	68 (3 %)	69 (3 %)
7	26 (1.29 %)	35 (1.74 %)	39 (1.93 %)
8	23 (1.14 %)	22 (1.09 %)	14 (0.69 %)
9	10 (0.5 %)	25 (1.24 %)	6 (0.3 %)
10	5 (0.25 %)	27 (1.34 %)	0 (0.0 %)
11	6 (0.3 %)	16 (0.79 %)	0 (0.0 %)
12	4 (0.2 %)	6 (0.3 %)	0 (0.0 %)
13	0 (0.0 %)	4 (0.2 %)	0 (0.0 %)
14	1 (0.05 %)	2 (0.1 %)	0 (0.0 %)
15	1 (0.05 %)	4 (0.2 %)	0 (0.0 %)
16	0 (0.0 %)	2 (0.1 %)	0 (0.0 %)
17	0 (0.0 %)	0 (0.0 %)	0 (0.0 %)
18	0 (0.0 %)	1 (0.05 %)	0 (0.0 %)

Bracketed values represent the percentage of villages from the total village database ($n = 2,016$ villages)

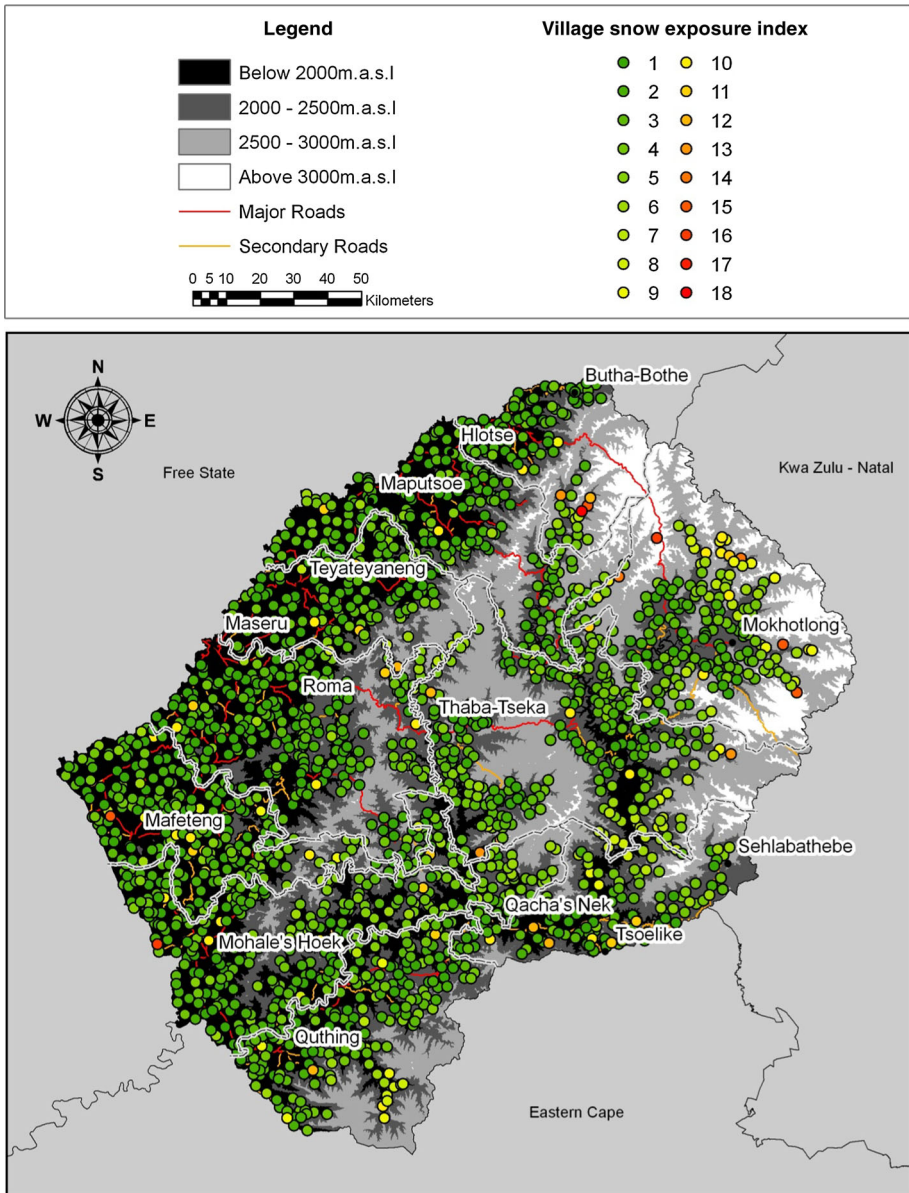


Fig. 7 An example of village exposure to prolonged snow cover across Lesotho during the mid-snow season (July/August). Exposure rankings are based on data collected for the years 2003–2010, and range from values of 1 (negligible exposure) to 18 (high exposure)

east-facing slopes (636). The cooler south-facing slopes are least favored with only 202 villages. Such geographic patterns of rural settlement likely reflect a preference toward the sunnier, warmer slopes (north-/east-facing exposures), than the more shaded and cooler south-/west-facing slopes, and are possibly also due to trends of snow longevity, which have direct consequences on livelihoods. The mean rate of snowmelt (within the first day after a snowfall) across all altitudes is

Table 11 Lesotho villages with the highest snow exposure rankings for the early, mid-, and late snow seasons, based on snow data from 2003 to 2010

Village	District	Exposure ranking
<i>Early season</i>		
Anone	Quthing	15
Aupolasi	Mokhotlong	14
Liteleng	Butha-Buthe	12
Setleketseng	Butha-Buthe	12
Thaba-Khubelu	Mokhotlong	12
Thopo	Butha-Buthe	12
Bolula	Mokhotlong	11
Ha Makepe	Mokhotlong	11
Ha Matsumunyane	Leribe	11
Ha Ranqhongoana	Mokhotlong	11
<i>Mid-season</i>		
Thoteng	Butha-Buthe	18
Letseng-la-Terae	Mokhotlong	16
Mabalane	Butha-Buthe	16
Liteleng	Butha-Buthe	15
Ha Rannini	Mafeteng	15
Letseng	Mohale’s Hoek	15
Mohlanapeng	Butha-Buthe	15
Bahaoleng	Thaba-Tseka	14
Ha Kanone	Mokhotlong	14
Liqalaneng	Butha-Buthe	13
<i>Late season</i>		
Liphaleng	Leribe	9
Lithipeng	Mohale’s Hoek	9
Khotojieng	Thaba-Tseka	9
Likonyeleng	Quacha’s Nek	9
Ha Mashenephe	Quthing	9
Kopanong	Berea	9
Tsieng	Maseru	8
Matsabeng	Mokhotlong	8
Lehlananeng	Butha-Buthe	8
Lumang	Thaba-Tseka	8

highest on north- and east-facing slopes (avg 40–50 %/day), followed by west- (avg 32–45 %/day) and south-facing (avg 10–37 %/day) aspects.

5.8 Spatial relationships between villages/settlements and their exposure to snow

Most villages in Lesotho are located below 2,000 m a.s.l and are concentrated in the western lowlands and the Senqu River Valley. Altitudes above 2,500 m a.s.l for all mountain ranges are sparsely inhabited, although 43 villages are located above this altitude in the districts of Mokhotlong, Butha-Buthe, Thaba-Tseka, Qacha’s Nek, and Quthing. With snow occurring relatively infrequently and melting rapidly at lower altitudes, the

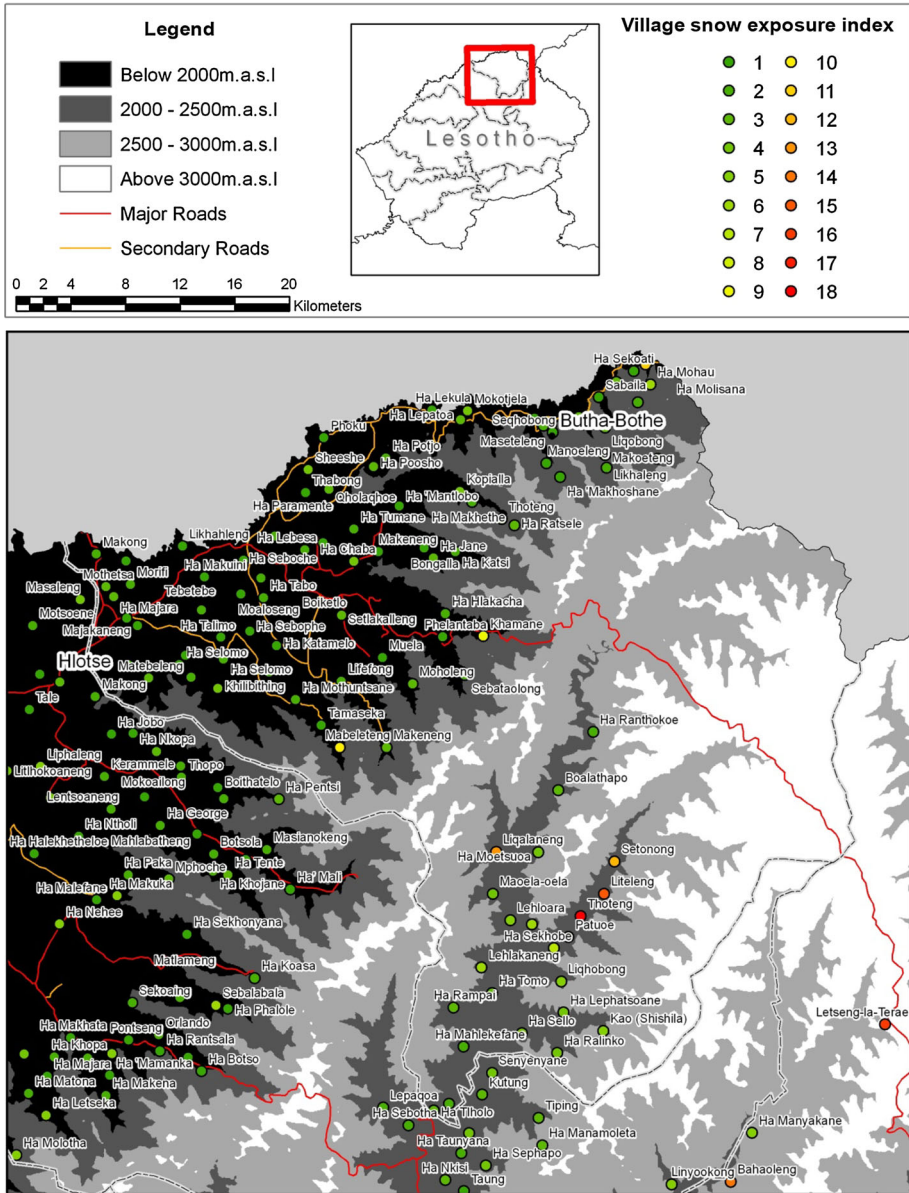


Fig. 8 An example of village exposure to prolonged snow cover for the Buthe-Buthe region of Lesotho during the mid-snow season (July/August). Exposure rankings are based on data collected for the years 2003–2010 and range from 1 (negligible exposure) to 18 (high exposure)

majority of villages thus have a low exposure to snow index. However, based on topographical maps of villages and transport routes, several major roads traverse high-lying terrain in the Maluti Range (>3,000 m a.s.l.), the Thaba Putsoa Range (>2,500 m a.s.l.), and the Central Range (>2,500 m a.s.l.). Secondary roads are located on mountainous terrain in the Central Range (>2,500 m a.s.l.) and on the escarpment south of Mokhotlong (>3,000 m

a.s.l). Villages and settlements connected by such high-lying major and secondary roads are thus more regularly impacted by snow, primarily through isolation and disconnection with the ‘outside’ world, and occasionally, this may be the case for extended periods lasting several days to weeks.

6 Discussion and conclusion

Many environmental hazards are unpredictable in terms of their spatial impact, speed, or duration (Cova and Church 1997). However, with remotely sensed imagery highlighting spatial changes over time, information on the changing size, extent, and influence of hazardous events may be provided, thus creating an opportunity to map the extent of geophysical threats and delineate areas that may be affected by such events (Espizua and Bengochea 2002). Snow-related hazards are a widely reported global phenomena (Margreth and Funk 1999; Gruber and Bartelt 2007; Pinto et al. 2007; Podolskiy et al. 2010; Prior and Kendon 2011), yet little is known about the *potential* spatial and temporal vulnerability of individual villages/settlements to snow hazards in less-developed rural regions, such as those in parts of central Asia, the Middle East, South America, and, indeed, Africa.

In our study, satellite images depicting snow cover have been integrated with the ground-based spatial data in a GIS, from which the potential village exposure to snow (i.e., *potential* vulnerability to snow) is determined for Lesotho. While village exposure to prolonged snow cover is apparently low through most of Lesotho, the occurrence of associated human and/or livestock deaths is a concern that needs to be addressed. It is notable that the spatial context of village/district exposure (*potential* vulnerability) to snow changes temporally through the snow season, such that the central and northern mountain districts are those most impacted during the early snow and mid-snow seasons, and the southern mountain regions during the late snow season. To this end, the potential exposure to snow rankings presented in this paper should at least serve to direct future evacuation or relief efforts, particularly in the case of widespread heavy snow events which have a return period of ca 4–5 years.

The spatiotemporal assessment of village exposure to snow presented in this paper falls within the aims set out by the International Strategy for Disaster Reduction in Africa, which has called for improving the following: (a) the assessment and identification of hazards, (b) the contribution to risk reduction through mitigation, and (c) the enhancement of effective emergency response management in Lesotho (ISDR 2004). Further, the identification of natural hazards to vulnerable communities in Lesotho is essential, particularly given the projected future climate changes with associated increases in extreme events (IPCC 2007; Obioha 2010). Our work is thus in accordance with the framework of the Southern Africa Vulnerability Initiative (SAVI), which aims to assess local vulnerability to multiple stressors (O’Brien et al. 2009). The mapping of seasonal snow cover over Lesotho should also contribute to the assessment of communities and regions that may be affected by climate change, which is one of the key requirements of the National Adaptation Programme of Action in Lesotho (NAPA 2006). The assessment of regional vulnerability in Lesotho on a countrywide scale has implications for food security, through the identification of areas with significant snow cover potential (Mock 2005). The identification of seasonal and spatial snow risk is an important initiative to reduce livelihood risks through improving disaster preparedness. Ideally, the assessment of seasonal exposure to snow should enhance the spatiotemporal management and response to snow-related human vulnerability in settlements across Lesotho.

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