The Geographical Journal of Nepal
Vol. 15: 23-40, 2022
DOI: https://doi.org/10.3126/gjn.v15i01.42884
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Changing precipitation patterns in far-western Nepal in relation to landslides in Bajhang and Bajura districts

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Received: 01 August, 2021; Accepted: 07 October, 2021; Published: March, 2022

Abstract

The geologically young terrains of the Nepal's Lesser Himalaya are strongly affected by the multiple and interrelated geo-hazards of landslides, floods, and debris torrents. One of the main factors that trigger these hazards is the duration and intensity of monsoon rainfall. Here, we interrogate precipitation data for a variety of different periods, the longest of which comprises 40 years (1977-2017) of annual rainfall data, for 17 rainfall stations in far-western Nepal. The average rainfall over the past 10 years (2007-2017) was found to be declining for most stations. The summer monsoon season (i.e. June to September) accounts for 70–80% of the total annual rainfall, and is critical for agricultural production; but the vast majority of floods and landslides also occur during this time. Changes in daily rainfall magnitude and frequency are analysed. The intensity of rainfall during monsoon time was found to increase by over 100% in the past 40 years, with this change especially pronounced in 2008. The variation of intensities of rainfall in relation to landslides at different elevations has also been explored. We found that rainfall intensity increased by 40–60% over an increase in elevation from 1 to 2 km in the study area of the Bajedi landslide in far-western Nepal.

Keywords: Landslide, rainfall intensity, far-western Nepal, monsoon

Introduction

Assessments of landslide risk require a detailed understanding of the historical and current causes that may trigger landslides. The purpose of studying rainfall is to identify whether it is the root cause that triggers landslide activity, or merely acts as an important antecedent. Nepal is the 20th most severely affected country by multi-hazards in the world (UNDRR, 2019). Over a distance of just 200 km, elevation changes from 70 m to 8848 m. This spatial variation together with highly rugged topography and soft, friable rocks, makes the country highly vulnerable to water-induced hazards such as landslides, soil erosion, floods, and debris torrents (Dahal, 2012). There are generally two main factors that trigger landslides: one natural and the other anthropogenic. Inherent natural factors include geological formation and structure, slope, aspect, land cover and ground cover conditions. External factors include earthquakes and rainfall duration/intensity. Anthropogenic factors include human interventions like deforestation, improper land use, unplanned construction and unplanned mining etc. In Nepal, the greatest number of landslides occurs in the monsoon season (Petley et al., 2007). Recently, bulldozer action on numerous unplanned roads in the Lesser Himalaya has acted as an important new landslide trigger. When we study the rainfall and its impact on landslides, it is important first to understand prior land use changes, and whether rainfall acts as a trigger or antecedent factor such as increasing soil saturation and pore-water pressures (Upreti, 2000; 2001).

Thus, an assessment of landslide risk requires understanding the historical and current causes that may trigger landslides. The purpose of this study is to understand whether landslide activity in a specific study area is largely governed by rainfall or by other causes. At the same time, we attempt to foster local awareness of landslides, their varied causes and their impacts on livelihoods. Far-western Nepal receives 70–80% of its annual precipitation during the monsoon season between June and September (Nayava, 1974; TCE, 2002), increasing the occurrence of landslides during this period of the year (Government of Nepal, 2019; World Bank, 2020). In a global landslide dataset, Nepal contributes 10% of all rainfall-induced landslide events, and 93% of all those triggered by seasonal monsoons (Froude & Petley, 2018). Furthermore, climate change has a direct influence on frequency and intensity changes of precipitation (Fischer & Knutti, 2015), thereby increasing the number of potential future landslides (Trenberth, 2011). Hence, it is necessary to understand the ways in which precipitation patterns are changing with time and the nature of their direct relationship with natural hazards such as landslides.

Landslides pose serious threats to lives and livelihoods, cause hundreds of fatalities each year (Figure 1), disrupt local agricultural productivity, damage infrastructure, and cause serious economic disruption both locally and nationally (Petley et al., 2007; Froude & Petley, 2018). Between 1971–2013, a total of 3208 landslide events were recorded, together with 4658 deaths, 623 missing people and affecting 0.59 million others indirectly, resulting in a direct economic loss of US$10.1m (Desinventar, 2020).

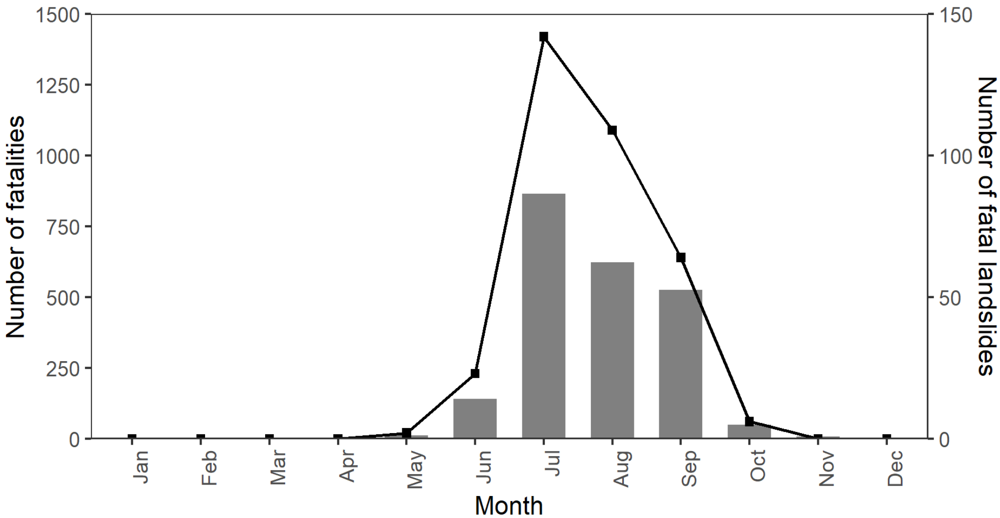


Figure 1: Comparison between the occurrence of landslide fatalities and the number of fatal landslides in Nepal for 1978–2005 (Petley et al., 2007).

There have been numerous detailed studies on the relationship between rainfall and landslides events in mountainous regions (Petley et al., 2007; Dahal, 2012; Froude & Petley, 2018; Kirschbaum et al., 2020). In hilly regions, landslides are triggered either from prolonged rainfall of several days to weeks (Gabet et al., 2004) or from short cloudbursts (Dixit, 2003). When rainfall infiltrates hillslopes, it changes pore water pressure, reduces shear stress, and can result in slope failure (Iverson, 2000).

Landslides are very much common during the summer monsoon in Nepal: failure is generally due to cessation of rainfall as well as its high intensity. Indeed, the 2020 summer monsoon may have been one of the wettest seasons in the past 50 years in Nepal. Nayava (2017) studied monsoonal rainfall in Nepal from 1971–2015; in this context, 2020 was unique in terms of rainfall intensity and the number of landslides triggered in the Lesser Himalaya. The total loss of life and property has not yet officially been declared by the Government of Nepal (GoN); however, the loss of property was assumed to be more than double that of 2019. Department of Hydrology and Meteorology reported that 2020 had the widespread wettest monsoon year. The average of daily accumulated precipitation during 2020 monsoon season indicated more than 9% than the normal accumulated precipitation in Nepal (DHM, 2021). We speculate that the very active local Monsoon season of 2020 could result from cleaner air arising from the Covid-19 pandemic (i.e. fewer flights and lower density of intensive transportation routes during national lockdown periods).

Monsoon-induced disasters such as landslides and pluvial flooding caused damage worth over US$ 17 million on national highways so far in 2020. Indeed, during the entire monsoon season in 2019, the total figure stood at US$ 11 million (Shrestha, 2020). Table 1 shows the impact of the most recent monsoon seasons on the human death and injury toll.

Table 1: Total fatalities, persons wounded and missing during the monsoon

Year	2016	2017	2018	2019	2020
Fatalities	487	588	455	406	177
Wounded	840	845	4188	1133	556
Missing	49	65	10	40	19

Source: Thapa, 2020

Much effort has been devoted to landslide and flooding risk reduction and resilience-building programmes in Nepal (MoHA, 2009). While absolute rainfall amounts are important triggers, in July 1993, a single high-intensity cloudburst (70 mm/hour) was responsible for widespread slope failure in the Kulekhani catchments (Dixit, 2003). Meanwhile, detailed studies on the relationship between rainfall and landslides events have been conducted elsewhere in eastern Himalayas, Darjeeling, and northern India. In one such Indian study, Froehlich et al. (1990) observed rainfall exceeding 50 mm, decreasing at a rate of 0.5 mm/min thereafter, when slides or slumps on steep slope segments began to occur, mainly along undercut sections of roads or rivers. In this case, over 130–150 mm fell in 24 hours or ~200–240 mm over a three-day period, leading to widespread landslide activity. This example is also applicable in the hills of Nepal. Recent studies in Sikkim province of India revealed that the threshold relationship for rainfall intensity is 1.82 mm/hour during the monsoon period in that region. In addition, an average precipitation of 1.05 mm/hour appeared to be sufficient to cause mass movement for fully-saturated soils during the monsoon (Bappaditya et al., 2019).

The purpose of this paper is to accrue a new compendium of rainfall data, and to analyse spatiotemporal changes in intensity and frequency in terms of changes in landslide dynamics. The remainder of the text is structured as follows. Section 2 introduces our study area in far-western Nepal, discusses rain gauge data availability and our methodology for analysing these data. Section 3 presents results of changes in precipitation; Section 4 then relates these changes to contemporaneous changes in landslide activity. Section 5 discusses these patterns in terms of regional effects of climate change; and, finally, Section 6 offers brief conclusions and a future outlook.

Methodology

The study area

This study is focused on two districts, Bajhang and Bajura, in the far-western region of Nepal (Figures 2a, 2b and 3a, 3b). Both districts are characterised by extremely rugged topography in the Lesser Himalayan Sequence (Cieslik et al., 2019), with an elevation ranging from 720–6960m. The specific study sites are the Bajedi and Sunkuda landslides in the Bajura and Bajhang districts, respectively. Both locations experience seasonal shallow slides (<1 m depth): rockslides in Bajedi and soil slides in Sunkuda.

The total area affected by deep-seated gravitational slope deformation (DSGSD) is about 29.8 km^2 at elevations of 950–2150 m. The bedrock is characterised by a series of overlapping quarzites and phyllites. DSGSD generates loose material and debris flow with potentially severe consequences for the communities of the lower Budhiganga river valley. Though quartzites are mechanically strong and impermeable, they are nevertheless slowly affected by rainfall penetration (Amabile et al., 2018). Moreover, the Bajura district is characterised by a relatively high density of E-W-trending thrust faults, allowing a greater degree of percolation (Parajuli et al., 2020; Paul et al., 2020).

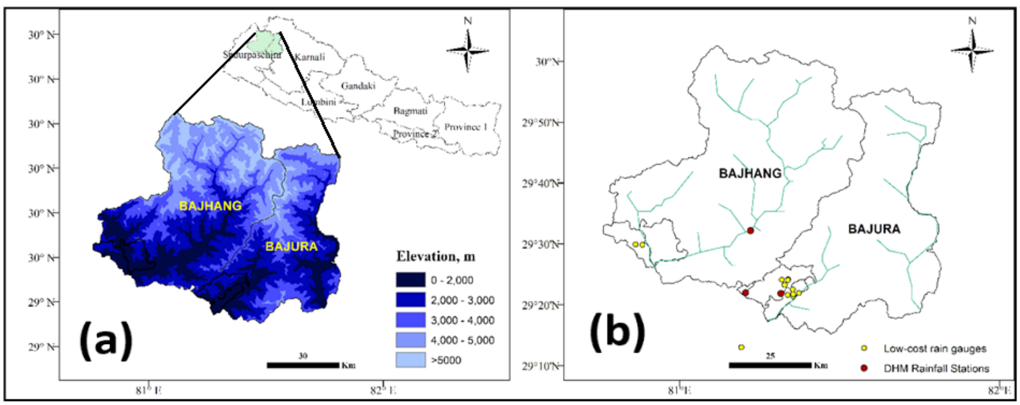


Figure 2: (a) Location map of the study area; (b) meteorological networks established by the Government of Nepal (GoN), Department of Hydrology and Meteorology (DHM); and community-owned automatic tipping-bucket rain gauges.

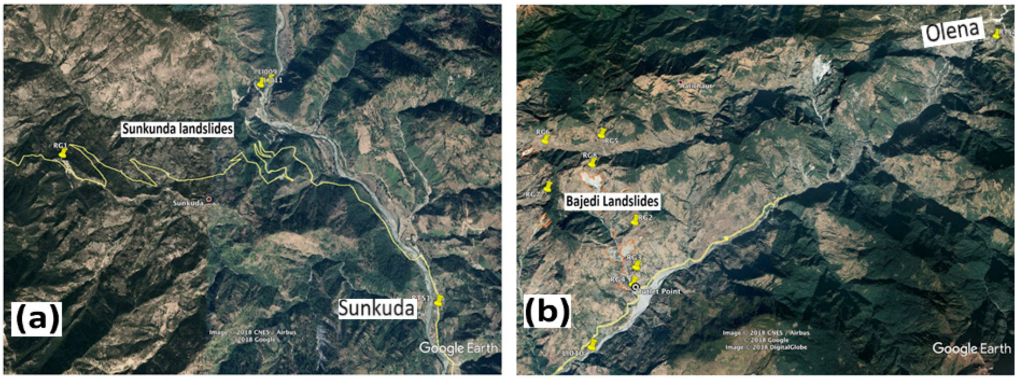


Figure 3: Location of landslides and meteorological networks (a) Sukunda landslide, Bajhang; (b) Bajedi landslide, Bajura .

Data availability

There are about 43 precipitation stations, which have been recording 24-hourly precipitation in the study area. All are manual rain gauges. Long-term data for the same period for all those stations are not available. In this study, 17 stations were selected. The long-term history of those 17 selected stations is personally known and verified; the time period of 1977–2017 has been considered based on these data. Mean monthly, seasonal and annual rainfall for all 17 stations for 1977–2017 were prepared and carefully evaluated. These data were extracted from the Government of Nepal (GoN), Department of Hydrology and Meteorology (DHM)'s internal databases. Among 43 rainfall stations, one station in Bajhang is close to the Sunkunda landslide, while another station in Bajura is within 1 km of the Bajedi landslide.

The hourly rainfall data was virtually not available in the study area; therefore, altogether, we installed another 13 automatic rain gauges at various locations (Figure 2b) in the landslide pilot area. Among these rain gauges, 12 are Davis 0.2 mm tipping bucket type (Davis Instruments Corp, 2017) fitted with a HOBO data logger. The remaining one is a Campbell Scientific 0.2 mm tipping bucket type, and is now operated by DHM. Ten of the gauges in the Bajedi area were installed on the associated landslide within a total area of 12 km^2. All 13 stations are considered for hourly data analysis. Current data availability is for a very short time frame i.e. from May to November 2019; only two stations contain the full 2019 rainfall time series.

Data analysis

Daily precipitation records of all stations were manually checked, compared with surrounding nearby stations, and outliers were screened. The mean, standard deviation and coefficient of variation of monthly and annual rainfall were calculated to check the rainfall variability. At the same time, mean monthly, seasonal and annual means of rainfall were also calculated. Simple linear regression (LOESS) was used to determine mean rainfall trends and coefficients of determination (R^2) for the significance of the trends. At the same time, statistical tools were used to check the rainfall variability of monthly and daily data (Arvind et al., 2017). Afterward, isohyets of average rainfall were generated for both long-term (1977–2007) and short-term (2007–2017) periods.

Rain gauges and seasonal rainfall

The seasonal rainfall at the two stations (Olena and Sunkuda) closest to the landslides in Bajedi of Bajura district is presented in Table 2. To visualise the patterns of rainfall in the study area, long-term data were tabulated and analysed along with four seasonal pattern of Nepal (Nayava, 1980): Winter (November-February), Pre-Monsoon (March-May), Monsoon (June-September), and Post-Monsoon (October).

Table 2: Seasonal rainfall at Olena and Sunkuda (2000–2017)

Station ID	Elevation	Winter (Dec-Feb)		Pre-Monsoon (Mar-May)		Monsoon (Jun-Sep)		Post-Monsoon (Oct-Nov)		Annual
	(m)	Mm	%	mm	%	mm	%	mm	%	mm
Olena	1116	106	9	197	16	878	72	36	3	1217
Sunkuda	894	67	6	166	14	939	76	57	5	1229

The Kolagaun station, representative of the region's mean elevation and slope aspects, was selected to elucidate the seasonal variation of rainfall from 1975–2017 (Figure 4). The long-term annual average rainfall here is 1825 mm; this station also represents well the extent of the landslides under consideration.

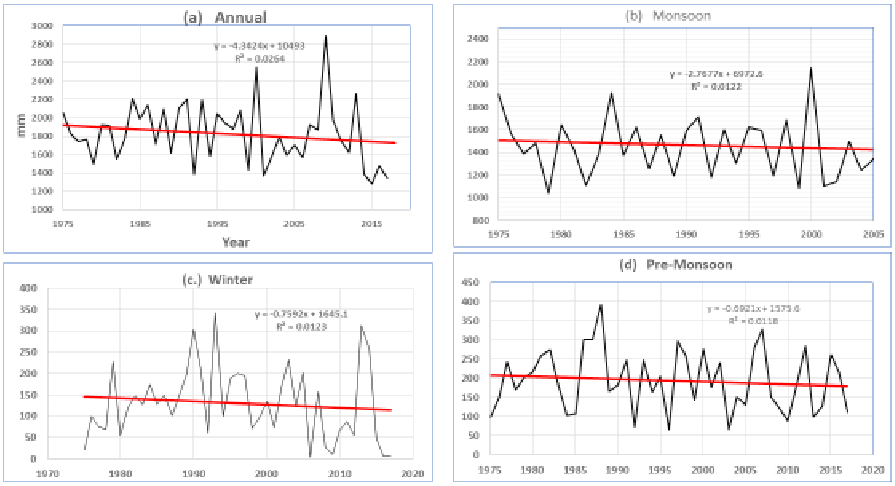


Figure 4: Trends of seasonal rainfall at Kolagaun, 1364 m elevation (a) pre-monsoon, (b) monsoon, (c) winter and (d) annual rainfall. Red line = trend line.

Figure 4 shows that rainfall decreases over all seasons. A post-monsoon panel is not represented, as it represents barely 1% of the total annual rainfall. These rainfall trends agree with those seen across the wider Hindukush Himalayas (Kieran et al., 2019). Moreover, they also agree with an observation of ~70% of springs running dry over the past eight years across western Nepal (Adhikari et al., 2020). Far-western Nepal is the only region of the country where mean rainfall has decreased appreciably over the past ~40 years (Nayava, 2004).

Characteristics of rainfall

Table 3 shows that, in general, there are fewer rainy days at lower elevations across the region. Also, higher elevation stations might register strong orographic precipitation trends resulting from westerly disturbances. The distribution of recently-installed automatic tipping-bucket rain gauge stations according to altitude is shown in Table 4.

Table 3: Rainy days (rainfall > 1 mm) for the four different seasons of far-western Nepal

Station	Elevation, (m)	Rainy days				
		Winter	Pre-Monsoon	Monsoon	Post-Monsoon	Annual
Jumla	2384	14	26	72	1	113
Kolagaun	1364	13	22	65	1	101
Dipayal	563	16	16	54	0	86
Dhangadhi	184	5	4	57	1	67

Table 4: Coordinates of 13 automatic tipping-bucket rain gauges installed in 2018–2019

Station ID	Latitude (DD)	Longitude (DD)	Elevation (m)
RG14	29.38	81.37	1020
RG4	29.37	81.35	1100
RG3	29.38	81.35	1162
RG17	29.50	80.87	1274
RG19	29.23	81.19	1400
RG11	29.38	81.33	1447
RG2	29.39	81.35	1524
RG1	29.50	80.85	1594
RG18	29.42	81.33	1860
RG12	29.42	81.33	1890
RG13	29.40	81.32	2030
RG15	29.40	81.32	2030
RG16	29.42	81.31	2042

Rainfall intensity

One of the most important aspects of analyzing rainfall in relation to landslide occurrence is rainfall intensity. We therefore selected the Kolagaun station, where intensity has demonstrated important variations over the past ~40 years, to analyze hourly rainfall patterns. Figure 5 shows that the intensity of rainfall is increasing, with a particular spike in 2009 (465.4 mm). In recent years, extreme events have been ascribed to the effects of climate change and a 50-year rainfall cycle; a peak in rainfall intensity was noted (Figure 5). Many places in that area have registered similar high intensities of rainfall with associated anecdotal evidence of high-magnitude pluvial flood events.

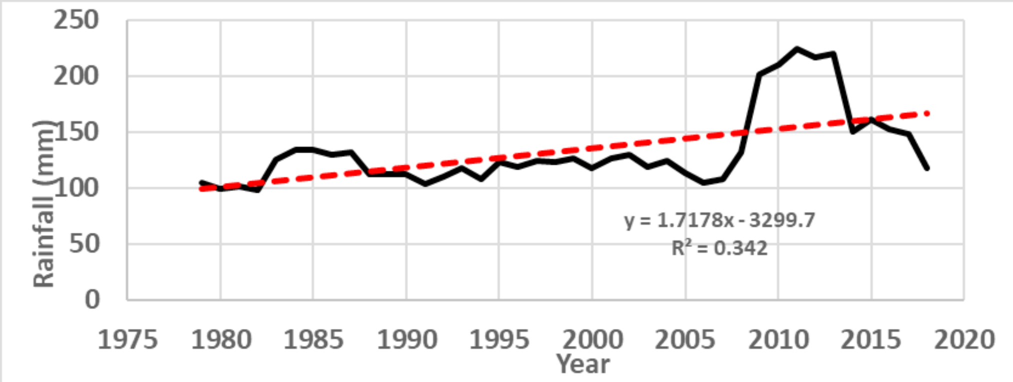
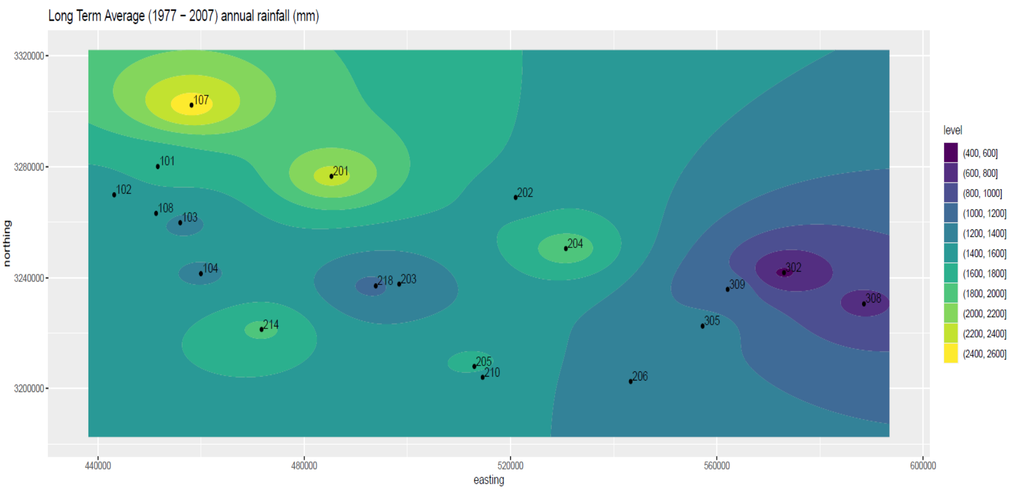


Figure 5: Five-year moving average (black line) of intensity of hourly rainfall (mm) at Kolagaun (1364 m elevation). Red line = 40-year trend.

Changing rainfall patterns in far-western Nepal

Long-term rainfall data from 1977–2017 and short term data from 2007-2017 for 17 stations of Western Nepal were considered. These data were also collected and analysed to visualise general patterns of rainfall at a broader scale. Figure 6 demonstrate the decreasing magnitude of rainfall across far-western Nepal.



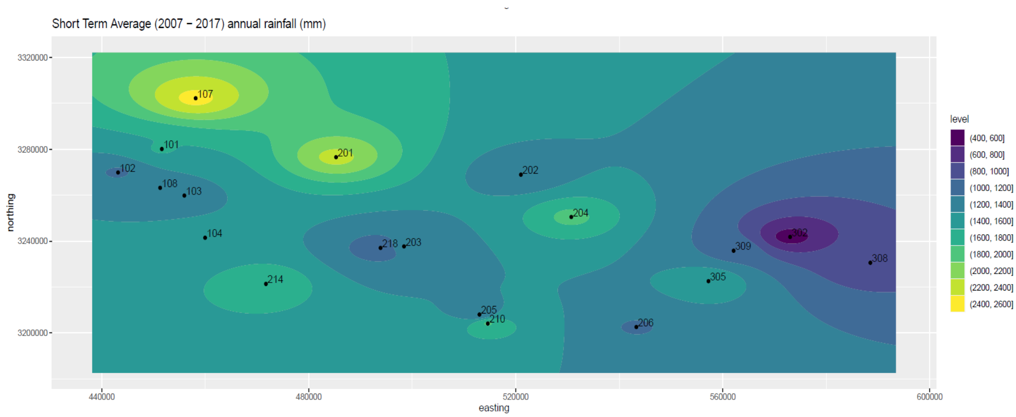


Figure 6: Long- (top) and short-term (bottom) mean rainfall for study area, far-western Nepal

Results and discussion

As already mentioned, data were not available virtually in the study area; therefore, we installed 13 automatic tipping bucket rainfall stations over a very small area (~42 km^2) with respect to slope, aspect and elevation (Table 4). To interrogate spatial rainfall patterns across the study area in greater detail, these more recent rainfall data were also retrieved, processed, and analysed. There are four categories of these new stations. There are only two stations in the Sunkuda landslide, both of which face northward (RG17 and RG1). Since we have only one season of rainfall at RG1, the rainfall distribution seems to agree with official DHM records; the total rainfall of the summer 2019 monsoon was 806.8 mm. Over that period, the rainfall intensity over any 24 hours was generally less than 40.0 mm (Figure 7a). Similarly, total rainfall registered by RG17 was similar, while daily rainfall intensity was less than ~50 mm throughout the 2019 monsoon.

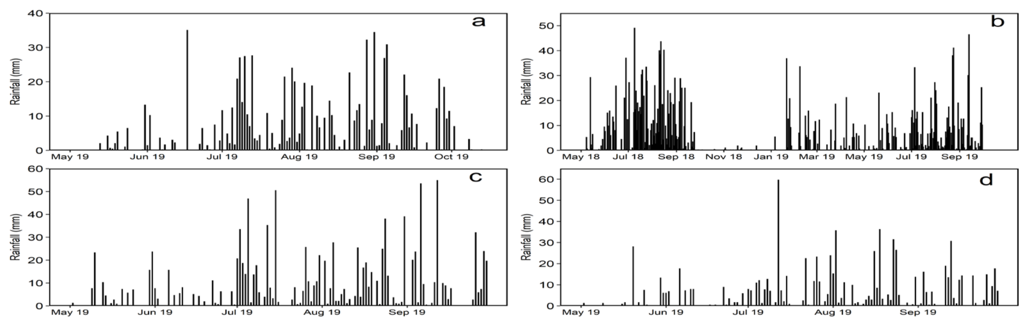


Figure 7: Daily rainfall totals at a) RG1, b) RG2, c) RG15 and d) RG14

The three valley-bottom stations are RG4, RG14 and RG19. For two days in July and September 2019, daily rainfall intensity exceeded 50 mm for RG14 and RG11. Meanwhile, five other stations are located directly on the Bajedi landslide, facing south: RG2, RG3, RG11, RG13 and RG15. The final three stations are situated in an elevated valley 3 km northwest of the Bajedi landslide: RG12 (1890 m elevation), RG18 (1860 m), and RG16 (2040 m). Table 5 summarises mean monthly rainfall totals for our newly installed automatic tipping-bucket rain gauges. In 2019, monsoon seasonal rainfall in far-western Nepal was slightly below normal levels (DHM, 2019).

Table 5: Monthly rainfall data from Davis rain gauges (mm)

Station	Elevation (m)	May	June	July	Aug	Sep	Oct	Nov
RG14	1020	60.4	75.8	343.8	250.4	192.6	0.8	0.2
RG11	1116	77.4	119.0	403.8	268.2	387.2	33.4	2.2
RG17	1274	-	76.2	347.8	263.2	151.2	-	3.4
RG11	1447	52.6	100.6	386.4	228.4	219.4	0.2	0.2
RG2	1524	77.2	62.4	370.6	245.2	246.8	1.0	0.2
RG1	1594	-	77.4	278.8	299.8	214.4	16.0	0.2
RG18	1860	-	78.0	315.4	-	-	-	-
RG15	2030	-	81.0	519.0	389.2	383.6	13.0	0.2
RG 16	2040	62.6	97.6	416.6	301.6	-	-	19.4

Relationship between landslides and rainfall

The number of days of rainfall in the immediate vicinity of the Bajedi landslide was 8–12 over the course of the 2019 summer monsoon. This figure rose to a peak of 23–25 days in July, followed by 20–25 in August, and 18–20 in September. We found a direct positive correlation between elevation and number of days in which rainfall was observed (Figure 8). The number of continuously rain days is arguably the key metric determining landslide occurrence (Petley et al., 2007).

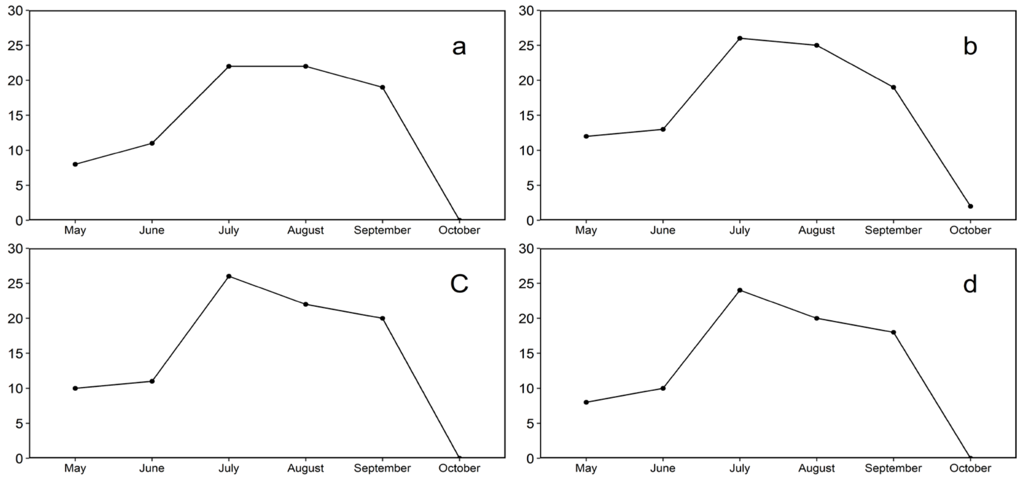


Figure 8: Number of rainy days during the 2019 monsoon registered by a) RG14, b) RG15, c) RG11, and d) RG2.

Similarly, the intensities of rainfall at the same stations over periods of 1, 2, 3, 6 and 12 hours are shown in Figure 9. The variation of intensities of rainfall over 1–12 hr was 18–76 mm at RG2 (1524 m). For a typical higher-elevation station, RG13, this range increased to 47–127 mm. This strong variation across a single landslide validated our methodology of choosing multiple installation sites of increasing elevations up the landslide.

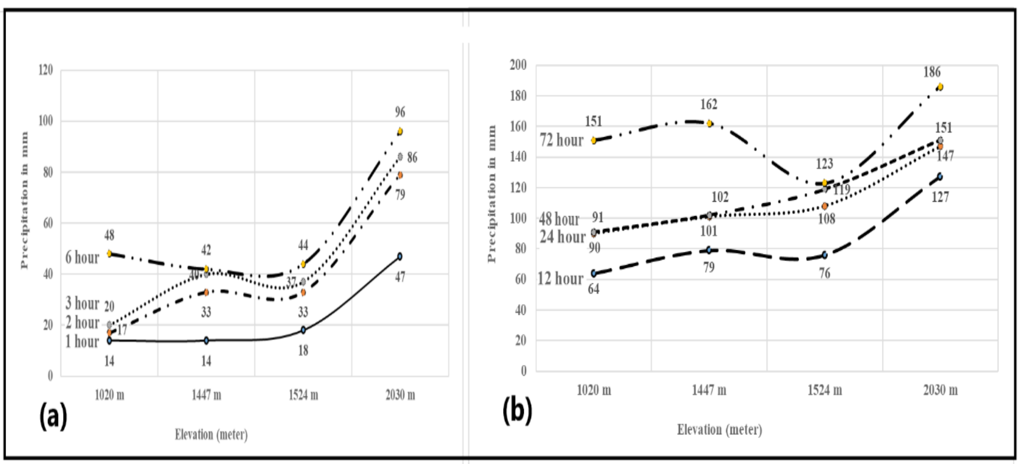


Figure 9: Rainfall intensities by elevation; (a) 1, 2, 3, 6 hours; (b) 12, 24, 48, 72 hours

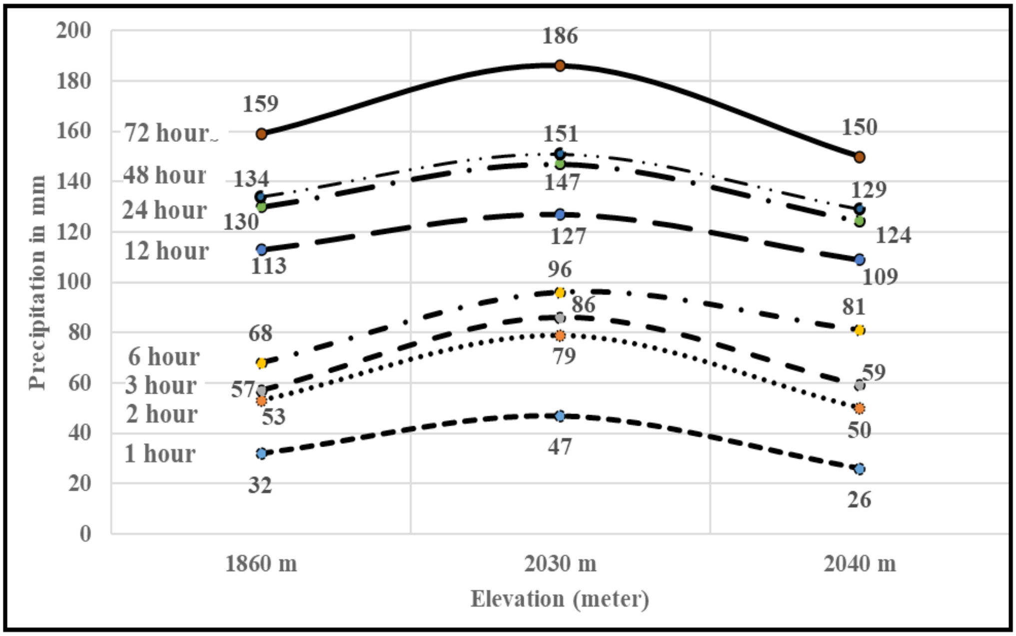


Figure 10: Rainfall intensities by elevation at 1, 2, 3, 6, 12, 24, 48, and 72 hours – averaged in July 2019 (1860 m and 2040 m on leeward side, and 2030 m on windward side).

Figure 10 clearly indicates that rainfall intensities recorded on the leeward side of a hillslope are lower than the equivalent totals on the windward side. DHM derived that the threshold values for flood forecasting were 60, 80, 100 and 120 mm of rainfall over 1, 2, 3, and 24 hours respectively (DHM, 2019). The rainfall intensities recorded by RG13 (Figure 9) generally exceed these threshold values. Elsewhere, rainfall intensity recorded by RG2 over 24-, 48-, and 72-hour periods was 60 mm, 91 mm, and 145 mm, respectively. For RG15 these values were 112 mm, 148 mm, and 178 mm (Figure 9). Less rainfall was recorded on the leeward side of the hillslope (Figure 10).These values of rainfall intensity are "very high" in terms of mean monsoon rainfall across Nepal (DHM, 2019), suggesting a strong correlation with the high density of nearby landslides. The region's fragile and friable Miocene stratigraphy must be considered, along with over-zealous and unplanned road building, for development purposes. We discussed these factors with local community members at both study sites, explaining that the dominance of agricultural land correlates with greater-magnitude mudslides, which would have an important negative impact on local livelihoods and community cohesion.

Cumulative rainfall variation over 1, 2, 3, 6, 12, 24, 48, and 72-hour periods across the study area (which changes in elevation from 1020 m to 2030 m) was 14 mm, 47 mm, 48 mm, 96 mm, 64 mm, 151 mm, 127 mm, and 186 mm, respectively. When one considers stations on leeside hillslopes only, the variation over 24, 48, and 72-hour periods was 32 mm, 130 mm, and 159 mm, respectively. We speculate that the very active local monsoon season of 2020 could result from cleaner air arising from the Covid-19 pandemic (i.e. fewer flights and lower density of intensive transportation routes during national lockdown periods), a causal relationship that warrants further investigation. In far-western Nepal, the link to enhanced landslide activity was important, with a spike in fatalities and damage over 2019 and 2020 (Thapa, 2020). Landslide-damaged property losses were estimated at over US $20 million, or double the total for 2018.

Understanding landslide risk necessitates an understanding of historical and current triggers, and the way in which their influence has waxed and waned over time. We also created an awareness of rainfall-induced landslides amongst the local communities, as well as their potential impacts on livelihoods, especially as several of the rain gauge stations were established within secondary school compounds (for additional security and maintenance purposes). This latter point allowed us to share our results with local educators and students and to introduce practical sessions using measuring cylinders to collect local household estimates of daily rainfall (Paul et al., 2020). This technique has been demonstrated to be very powerful in general awareness-raising of local landslide risk; the local community are better equipped to observe landslides themselves, and then to share inputs into local and regional disaster risk reduction (DRR) plans (Paul et al., 2018; Cieslik et al., 2019). Furthermore, we were also able to extend our rainfall sampling campaign and data analysis to collect data from 126 households in Bajura and 36 households in Bajhang, containing comprehensive information on demography, landslides and local resilience issues etc. This enabled us to link social/municipal data to rainfall metrics to produce a series of DRR recommendations for local municipal councils (Budhi Ganga, Chededaha, and Birthachaur rural municipalities). Subsequent discussions of general antecedents and triggers for local landslides, and their potential effects, enhanced local-level resilience and long-term capacity (especially allied to our work in local secondary schools).

Conclusions

Rainfall patterns in far-western Nepal exhibit important annual decreases over all seasons, especially winter rainfall, which is decreasing indeed across the entire Hindukush Region. Recent reports of springs drying up across western Nepal are also corroborated by the results of our study. In addition, we have demonstrated that rainfall intensity is increasing, which may lead to a greater range of hazards such as rapid flooding and more rapid and regular onset of landslides, especially in the local geologically fragile terrain (Miocene metaphyllites). We observed that rainfall intensities at lower elevations may not have reached assumed threshold values, but the highest-elevation station at (2030m) registered significantly more rainfall than the associated threshold. If rainfall is uniformly continuous for 24-, 48-, and 72-hour periods, and the total cumulative rainfall exceeds 120 mm, landslide events are likely to result, the effects of which being exacerbated by antecedent high soil saturations of that area, leading to massive mudslides. Therefore, when dealing with threshold values for flood forecasting or landslides, one should consider not only the rainfall registered by a single station, but also the probable rainfall over different elevations in the particular area, to give a more plausible and robust result. Otherwise, misleading early warnings may occur. We also suggest that engaging communities local to a particular landslide – for instance, by installing rain gauges in school compounds, or by conducting village discussion sessions – enhances local resilience and capacity against potentially lethal landslides and flood events.

Acknowledgements

We acknowledge funding from the UK Natural Environment Research Council (NERC) and Department for International Development (DFID) (contract NE/P000452/1) under the UK SHEAR (Science for Humanitarian Emergencies and Resilience) program (grant number NE/P000452/1). We also acknowledge the GoN Department of Hydrology and Meteorology (DHM) for their never-ending support in providing data.

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