DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

Proceedings
of the 7th International Conference

Chengdu, China, 23–27 September 2024

Edited by
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Geomarketing LLC
Moscow
2024

СЕЛЕВЫЕ ПОТОКИ: катастрофы, риск, прогноз, защита

Труды
7-й Международной конференции

Чэнду, Китай, 23–27 сентября 2024 г.

Ответственные редакторы
С.С. Черноморец, К. Ху, К.С. Висхаджиева

ООО «Геомаркетинг»
Москва
2024

泥石流：

灾害、风险、预测、防治

会議記錄

第七届国际会议

中国成都, 2024年9月23日至27日

編輯者
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Geomarketing LLC
莫斯科
2024

УДК 551.311.8
ББК 26.823
С29

Debris Flows: Disasters, Risk, Forecast, Protection. Proceedings of the 7th International Conference (Chengdu, China). – Ed. by S.S. Chernomorets, K. Hu, K.S. Viskhadzhieva. – Moscow: Geomarketing LLC. 622 p.

Селевые потоки: катастрофы, риск, прогноз, защита. Труды 7-й Международной конференции (Чэнду, Китай). – Отв. ред. С.С. Черноморец, К. Ху, К.С. Висхаджиева. – Москва: ООО «Геомаркетинг», 2024. 622 с.

泥石流：**灾害、风险、预测、防治. 會議記錄 第七届国际会议. 中国成都.** 編輯者 S.S. Chernomorets, K. Hu, K.S. Viskhadzhieva. – 莫斯科: Geomarketing LLC. 622 p.

ISBN 978-5-6050369-6-8

Ответственные редакторы: С.С. Черноморец (МГУ имени М.В. Ломоносова), К. Ху (Институт горных опасностей и окружающей среды Китайской академии наук), К.С. Висхаджиева (МГУ имени М.В. Ломоносова).

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При создании логотипа конференции использован рисунок из книги С.М. Флейшмана «Селевые потоки» (Москва: Географгиз, 1951, с. 51).

Conference logo is based on a figure from S.M. Fleishman’s book on Debris Flows (Moscow: Geografgiz, 1951, p. 51).

Debris flow phenomenon: A potential outcome of the changing climatic pattern in Northern Pakistan

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Abstract. Climate change is not a theory, we are currently undergoing an era where it is being experienced. The 2022 catastrophic rains and the resultant destruction they caused in Pakistan are seen by the experts as a glimpse of what lies ahead. Like other parts of the world, the changing climatic patterns are going to influence Pakistan in a number of ways including their impact on natural disasters in the country. Studies have projected the rates of warming in Pakistan greater than the global average. The 2022 field campaign of Geological Survey of Pakistan carried out in Gilgit-Baltistan observed that debris flows constituted about 75% of the mass-movement hazards in response to July-August catastrophic rains; about 100% of the mass-movement related casualties were caused by the debris flow phenomenon; anthropogenic activities further aggravate the situation by inducing the mass movement phenomenon. The increasing debris flow events will not only affect the local communities but will also have long-term effects on the downstream communities e.g., enhanced rates of sedimentation will reduce the storage capacities of downstream water reservoirs. A clear relationship has been observed between debris flow events and the stream gradient but a number of other factors need to be considered as well. Much more work needs to be done for a reliable debris flow hazard assessment and mitigation strategies in northern Pakistan.

Key words: *debris flow, climate change, precipitation, catchment, digital elevation model*

Cite this article: Sadiq S., Janjua M.A., Ali H., Awan A.A. Debris flow phenomenon: A potential outcome of the changing climatic pattern in Northern Pakistan. In: Chernomorets S.S., Hu K., Viskhadzhieva K.S. (eds.) Debris Flows: Disasters, Risk, Forecast, Protection. Proceedings of the 7th International Conference (Chengdu, China). Moscow: Geomarketing LLC, 2024, p. 429–444.

Феномен селевых потоков: потенциальный результат изменения климатического режима в Северном Пакистане

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Аннотация. Изменение климата — это не теория, в настоящее время мы переживаем эпоху, когда это происходит на собственном опыте. Катастрофические дожди 2022 г. и вызванные ими разрушения в Пакистане рассматриваются экспертами как проблеск того, что ждет нас впереди. Как и в других частях света, изменение климатических условий будет влиять на Пакистан различными способами, включая воздействие стихийных бедствий в стране. Согласно исследованиям, темпы потепления в Пакистане превышают среднемировые. В ходе полевой кампании Геологической службы Пакистана, проведенной в Гилгит-Балтистане в 2022 г., было отмечено, что селевые потоки составляют около 75% опасных массовых явлений, вызванных катастрофическими дождями в июле-августе; около 100% жертв, связанных с массовым движением, были вызваны селевыми потоками; антропогенная деятельность еще больше усугубляет ситуацию, провоцируя массовое движение. Участившиеся случаи схода селевых потоков не только затронут местное население, но и окажут долгосрочное воздействие на расположенные ниже по течению населенные пункты, например, увеличение скорости осадконакопления приведет к снижению емкости водохранилищ, расположенных ниже по течению. Наблюдается четкая взаимосвязь между селевыми потоками и уклоном потока, однако необходимо учитывать и ряд других факторов. Для достоверной оценки опасности селевых потоков и разработки стратегий смягчения их последствий в северном Пакистане необходимо проделать еще много работы.

Ключевые слова: *Селевые потоки, изменение климата, осадки, водосбор, цифровая модель рельефа*

Ссылка для цитирования: Садик С., Джанджуа М.А., Али Х., Аван А.А. Феномен селевых потоков: потенциальный результат изменения климатического режима в Северном Пакистане. В сб.: Селевые потоки: катастрофы, риск, прогноз, защита. Труды 7-й Международной конференции (Чэнду, Китай). – Отв. ред. С.С. Черноморец, К. Ху, К.С. Висхаджиева. – М.: ООО «Геомаркетинг», 2024, с. 429–444.

Introduction

Pakistan being located in a tectonically active regime present the development of plate boundaries that involve collision, subduction, obduction and strike-slip faulting a variety of plate boundaries [*Farah et al., 1984*]. Northern Pakistan is prone to seismic and mass movement hazards due to its particular terrain and tectonic setup; mass movement phenomenon ranges from rockfall, slides, debris flow, snow avalanche and Glacial Lake Outburst Flood (GLOF). Many studies have documented the plenty of landslides in the region [*Ahmed et al., 2015; Akhtar et al., 2017; Basharat et al., 2014; Hewitt, 1998, 1999; Hussain & Awan, 2009; Latif et al., 2013, 2015, 2016; Nash et al., 1985; Owen et al., 1996; Sadiq et al., 2012, 2021; Sadiq & Momose, 2017; Sadiq & Shah, 2016a, 2016b; Sato et al., 2007; Shroder & Bishop, 1998; Torizin et al., 2018*]. These hazards continuously pose a threat to life and infrastructure in Gilgit-Baltistan, Azad Kashmir and Khyber Pakhtunkhwa regions of Pakistan; they not only transform the landform through slope denudation [*Gilchrist et al., 1994*] also affect the communities either through stream blockage and/or excessive sedimentation [*Hewitt, 2006; Korup, 2004, 2005; Roering et al., 2005*].

The areas affected by mass movement induced by 2022 catastrophic rains in Gilgit-Baltistan province were visited on the basis of information gathered from local administration. Almost all the cases were reported along the Karakoram Highway (KKH), Nagar District (Nagar and Bar valleys), Ghizer Valley, Ishkomen Valley and Yasin Valley; so, these areas were covered through brief field visits at each site to gather first-hand information of the events. All these areas are drained by Ghizer and Hunza rivers (Gilgit River is another name for the Ghizer River). Fig. 1 presents the location plan of the above-mentioned areas in the context of Pakistan's country map.

Gilgit-Baltistan's elevation ranges from 918-8392 meters above sea level (Fig. 1*b*). The climate greatly impacted by its mighty mountain ranges; the eastern portion comprising western Himalayas is relatively moist but northern and north-western parts comprising Karakoram and Hindukush ranges are out of the reach of monsoon rains, and present a dry climate [*Ashraf et al., 2014*]. The Himalayan regions may be classified as semi-arid while the northern and north-western drier regions represent an arid climate. Based on the 1930–2019 data, the mean annual rainfall in Gilgit-Baltistan has been calculated 208 mm with April as the wettest month with 35 mm while the driest month is November that experiences only 5mm of average rainfall; similarly, the hottest month is July with 27.2 ºC average temperature while January being the coldest month has an average monthly temperature of 1.8 ºC [*Khan et al., 2020*]. Again, the mountainous terrain offers much variation in precipitation level over a short geographic distance. The total ice reserves in Pakistan contributed by Karakoram, Hindukush and Himalayan ranges are 87%, 10% and 3% respectively [*Ashraf et al., 2014*].

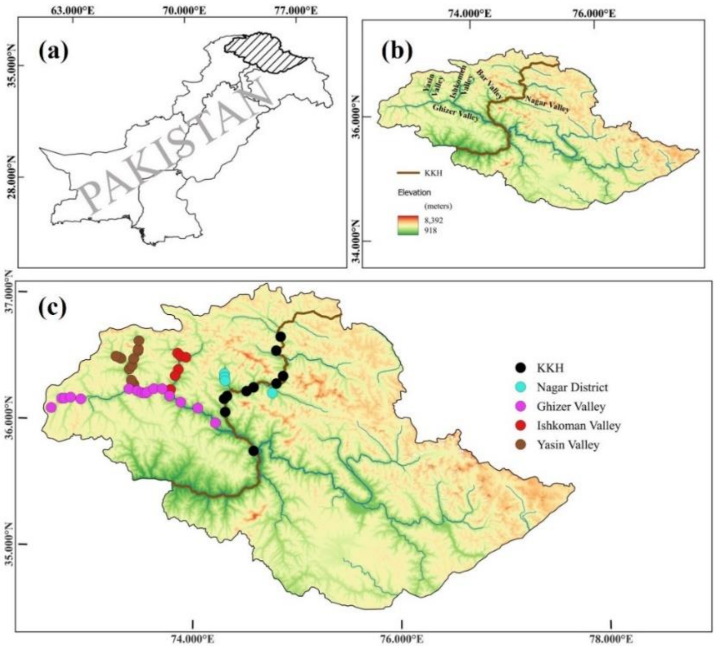

Fig. 1. Location map of the study area (a) map of Pakistan with Gilgit-Baltistan province as shaded area (b) location of KKH, Nagar, Bar, Ghizer, Ishkoman and Yasin valleys in Gilgit-Baltistan (c) location map of the sites visited during the current study

Problem statement

Climate change is a reality and a huge majority of climate scientists (97%) believe in human induced climate change [*AAAS, 2014*] while another study shows the percentage of earth scientists having consensus on the issue ranges from 91% to 100% [*Myers et al., 2021*]. Globally, the surface temperature has risen by 1.1ºC during 2011–2020 than that during 1850–1900 with notable rises over land as compared to over ocean [*IPCC, 2023*]. The Paris agreement emphasizes that increase in global average temperature should be curtailed below 2ºC while continuous efforts should be made to limit this increase to 1.5ºC [*Delbeke & Vis, 2019*]. Studies suggest that the world needs to drop the emissions at a rate of 2.7% annually (2020–2030) to meet the target of 2ºC and 7.6% annually for a 1.5ºC goal [*UNEP, 2019*]. Recently, a research organization presented very alarming results of their findings that the year 2023 being the warmest on the planet earth since 1850 have crossed the 1.5ºC threshold as 2023 was 1.54ºC (± 0.06ºC) warmer than the pre-industrial levels, commonly referred as the years between 1850–1900 [*Berkeley Earth, 2024*].

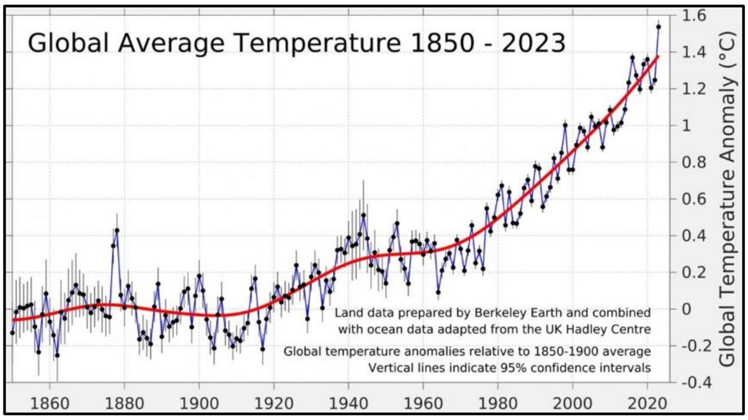

Fig. 2. Data presents the year 2023 as the warmest year since pre-industrial levels, crossing the much-debated threshold of 1.5ºC [*Berkeley Earth, 2024*]

Indus river basin partially shared by four countries (Pakistan, India, China and Afghanistan) falls mostly (about 52%) in Pakistan; mountainous terrain of Himalayas, Karakoram and Hindukush constitute the upper Indus basin while the southern plains form the lower Indus basin; projected values suggest an increase in temperature and precipitation in the Indus River basin [*Rajbhandari et al., 2015*]. The same study predicts that rainy days will increase in number in the upper basin while an increase in rainfall intensity associated with a decrease in the number of rainy days in the areas lying between the upper and lower basins. Although there are reservations about precipitation projections but most climate models suggest an increase in monsoon rainfall in Pakistan [*UNDP, 2017*]. Estimated increase in temperature is much higher in Pakistan that the projected global values [*Climate Risk Country Profile: Pakistan, 2021*]. In Pakistan 2022 Monsoon rains were exceptionally high, and experts saw it as a glimpse of what lies ahead in the scenario of changing climatic patterns. The rainy season prevailed during July-September with somewhat continuous precipitation in July and August; the Monsoon rains in 2022 were 175% above average rainfall in the country [*PMD, 2022*]; the total damage due to resultant flood have been estimated at USD 14.9 billion with a total loss of USD 15.2 billion [*Ministry of Planning Development & Special Initiatives, 2022*].

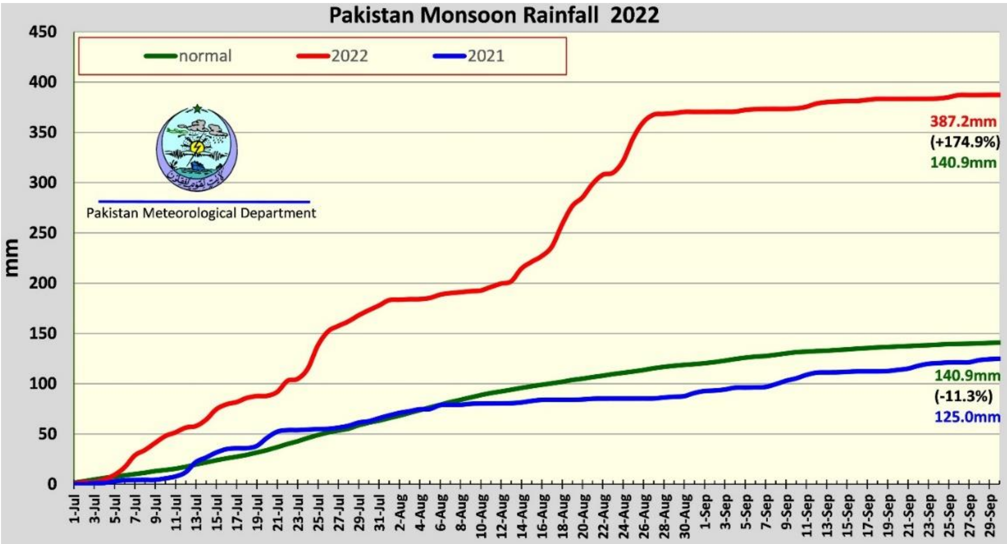

Fig. 3. Comparative rainfall during 2021 and 2022 versus the normal rainfall [*PMD, 2022*]

Now the anthropogenically induced change in climatic patterns is like a slow poison to the planet earth; a devastation comparable to any other in the earth's history; the situation may be compared with hydrogen bomb which may explode if current emission scenario is not dealt with [*Pierrehumbert, 2006*].

The climate change is going to affect the factors that impact our planet and life on it e.g., ecosystem, natural disasters, food and water availability, economy etc. Although it is difficult to build a relationship between landslides and climate as both operate on different scales (temporal and geographical) but an increase in rainfall frequency and intensity will trigger more landslides at least the shallow, rapid landslides (more deadly as giving less time to escape) including rockfall, debris flows, soil slips, small rock slides [*Gariano & Guzzetti, 2016; Jakob, 2021; Nyaupane & Chhetri, 2009; Palmer, 2020; Petley, 2012*]. Field visit in 2022 presented a very terrible picture of mass movement issues related to the abnormally high disastrous rains (Fig. 4).

Methodology

After collecting the available information through reconnaissance fieldwork, the data was analyzed; individual events were identified and organized (as far as possible) on the basis of mass movement type, disastrous impact, past history, and future potential. Being the far dominant mass movement type, debris flow was particular area of interest. Based on the available information, a weighing/ranking criterion for individual event was devised based on two parameters: (i) frequency of the event (ii) extent of destruction and volume of debris (2022 and prior known events). Each of the two parameters were further categorized into three classes: low, medium and high. For example, an event with less known frequency was placed in 'low' category of frequency and those with the highest frequency were placed in the 'high' category. Similarly, three classes were used for the second parameter. Each class was assigned a particular numeric value. The numeric values of 4, 7 and 10 were reserved for low, medium and high respectively. Then the weights were added for each event and the event was assigned a specific color based on the level of activity. Green, yellow and red colors represented low, medium and high levels of activity.

Fig. 4. A few glimpses of the destruction caused by 2022 rains

The ruggedness for individual catchments was calculated in the simplest way [*Melton, 1965*] by using the following ratio:

$$R = \frac{H}{\sqrt{A}},$$

where R is the ruggedness commonly termed as the Melton Ratio, H is the vertical relief of the catchment, A is the catchment area. Terrain Analysis toolbox (Channels and Hydrology) of the SAGA (System for Automated Geoscientific Analyses) was applied on Digital Elevation Model (DEM) to derive stream network, catchment, area and relief in order to calculate the Melton Ratio of individual catchments. After calculating Melton Ratio for every watershed, the mean values of Melton Ratio were calculated for the catchments falling in low, medium and high categories mentioned above.

Data

Stream information and basin ruggedness (Melton Ratio) form the basis of current study. Stream data was collected through fieldwork in the study area while temporal data from Google Earth was also used to identify some past debris flow events. 15 tiles of ALOS PALSAR were downloaded as elevation data for the calculation of Melton Ratio. For the generation of DEM for the whole Gilgit-Baltistan (Fig. 1*b* 28 tiles of SRTM were downloaded. Table 1 presents the details of the datasets used for the current studies.

Table 2. Data used in the current study

Data category	Name	Description	Source
Event Information	-	Occurrence time, causative factors, extent, damage caused, prior history	Field data collection including community interviews
			Google Earth
Digital Elevation Model	ALOS PALSAR	High resolution terrain corrected, 12.5 m resolution. Shuttle Radar Topography Mission (SRTM) or National Elevation Dataset (NED) resampled DEM used for Radiometrically Terrain Correction (RTC) processing	Japan Aerospace Exploration Agency (JAXA)
Digital Elevation Model	SRTM	SRTM (Shuttle Radar Topography Mission) 1 Arc-Second Global, version 3, 30m resolution.	USGS EarthExplorer

Analysis

10 events were recorded along KKH, 5 in Nagar District, 19 in Ghizer Valley, 10 in Ishkoman Valley and 16 in Yasin Valley (Table 2). Out of the 60 events in total, 52 corresponded to debris flow 6 to rock fall and 1 each to rockslide and land creep. Debris flow cover about 87% of the events, rock fall accounts for 10% while rockslide and land creep for 1% each (Fig. 5). Moreover, debris flow phenomenon was responsible for all the mass movement related casualties (17 casualties) in the visited areas.

Table 3. Area wise summary of mass movement types observed in the visited areas

Area (1st row) Mass movement type (1st column)	KKH	Nagar District	Ghizer Valley	Ishkoman Valley	Yasin Valley	Total
Debris Flow	8	5	15	8	16	52
Rockfall	1	–	3	2	–	6
Rock slide	1	–	–	–	–	1
Land creep	–	–	1	–	–	1
Total	10	5	19	10	16	60

As per ranking scheme mentioned in the methodology section, each and every debris flow event was classified in one of the three classes: low, medium and high represented by green, yellow and red colors respectively. As the study was focused on the disastrous events so the Table 3 is greatly dominated by red color while the green color is very rare. Out of 52 debris flow events 43 have been categorized as high hazard (red), 7 as medium hazard (yellow) and 2 as low hazard (green).

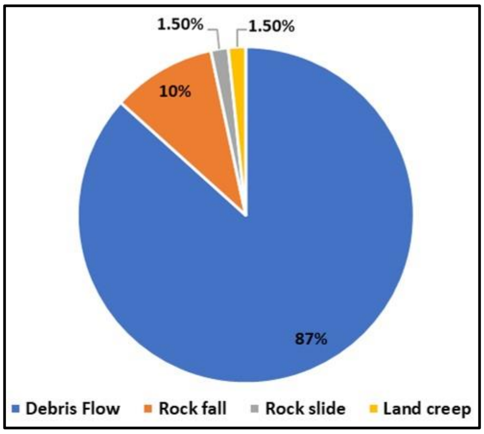

Fig. 5. Pie chart showing percentage of each mass movement type

Table 4. Categorization of individual debris flow events on the basis of parameters

Area	Locality		Type	Extent of destruction or debris transported (2022 and before)	Frequency	Overall rating	Loss of human lives in 2022	Level
KKH	Parri		Debris flow	10	7	17	–	
	Nomal		Rockfall	–	–	–	–	
	Goru		Debris flow	10	7	17	–	
	Jaglot Tunnel		Debris flow	7	10	17	–	
	Pissan village		Debris flow	–	–	–	–	
	Murtazabad Pyen		Debris flow	4	7	11	–	
	Attabad Tunnel-1		Rock slide	–	–	–	–	
	Shishkat		Debris flow	10	7	17	–	
	Khyber_2		Debris flow	7	7	14	–	
	Sost		Debris flow	10	7	17	–	
Nagar District	Hoper		Debris flow	10	7	17	–	
	Barbais		Debris flow	10	10	20	–	
	Bardas Nala		Debris flow	10	10	20	–	
	Barkot Nala		Debris flow	10	10	20	–	
	Dupas Nala		Debris flow	10	7	17	–	
Ghizer Valley	Henzal		Debris flow	4	7	11	–	
	Sherqilla Nala	Sherqilla	Debris flow	7	10	17	–	
		Bichar		10	7	17	7	
	Bubur		Debris flow	10	4	14	10	
	Gahkuch		Debris flow	4	7	11	–	
	Hoper Nala		Debris flow	10	10	20	–	
	Sumal Gah		Debris flow	7	7	14	–	
	Saro Gah		Debris flow	7	7	14	–	
	Raushan Gah		Debris flow	10	10	20	–	
	Gawote	Gawote-1	Debris flow	7	7	14	–	
		Gawote-2	Debris flow	10	10	20	–	
	Gupis		Debris flow	10	10	20	–	

Area	Locality		Type	Extent of destruction or debris transported (2022 and before)	Frequency	Overall rating	Loss of human lives in 2022	Level
	Khalti		Debris flow	10	10	20	–	
	Phander		Rockfall	–	–	–	–	
	Teru Bahach		Debris flow	4	7	11	–	
	Teru Bahach		Rockfall	–	–	–	–	
	Hilthi Nalah		Debris flow	7	10	17	–	
	Barsat		Rockfall (also a snow avalanche site)	–	–	–	–	
	Langar Nalah		Debris flow	10	7	17	–	
Ishkoman Valley	Hurakish		Rockfall	–	–	–	–	
	Daeen		Land creep	–	–	–	–	
	Asumber Nalah		Debris flow	7	4	11	–	
	Ishkamitar		Debris flow	10	7	17	–	
	Ishko-men Debris Flow Zone	Isk-DF1	Debris flow	7	10	17	–	
		Isk-DF2	Debris flow	7	10	17	–	
		Isk-DF3	Debris flow	7	10	17	–	
	Immit Mass Wasting Zone	Immit Rockfall Zone	Rockfall	–	–	–	–	
		Immit-1	Debris fall	10	7	17	–	
		Immit-2	Debris fall	10	7	17	–	
		Immit Halbar Gol	Debris fall	10	10	20	–	
Yasin Valley	Haltar Nalah		Debris flow	10	10	20	–	
	Damalgan Nalah		Debris flow	10	7	17	–	
	Gindai Nalah		Debris flow	7	4	11	–	
	Noah Nalah		Debris flow	10	10	20	–	
	Taus Chashma		Debris flow	10	7	17	–	
	Asumber Nala	Asumber Main	Debris flow	10	7	17	–	
		Miner-berg	Debris flow	10	7	17	–	

Area	Locality	Type	Extent of destruction or debris transported (2022 and before)	Frequency	Overall rating	Loss of human lives in 2022	Level
	Brum-berg	Debris flow	10	7	17	–	
	Shyote Nalah	Debris flow	10	10	20	–	
	Gunu Nalah	Flash flood, debris flow	4	4	8	–	
	Daspar Nalah	Flash flood, debris flow	4	4	8	–	
	Khaimith	Flash flood, debris flow	7	7	14	–	
	Garmish Barkulti	Debris flow	10	10	20	–	
	Silpi Nalah	Debris flow	7	4	11	–	
	Tarsat	Debris flow	10	10	20	–	
	Umalsat	Debris flow	10	10	20	–	
	Darkot_Nala	Debris flow	10	7	17	–	
	Dalgiram	Debris flow	10	10	20	–	

Average Melton Ratios of the catchments for events categorized in green, yellow and red categories was calculated as 0.5, 0.78 and 0.97 respectively (Table 4).

Table 5. Comparison of Melton Ration for catchments categorized as green, yellow and red

Area	Catchment name	Overall rating	Level	Melton ratio
Yasin Valley	Gunu Nalah	8		0.71
	Daspar Nalah	8		0.29
Mean Melton Ratio		0.50		
KKH	Murtazabad Pyen	11		1.74
Ghizer Valley	Gahkuch	11		0.65
–	Teru Bahach	11		0.63
Ishkoman Valley	Asumber Nalah	11		0.33
Yasin Valley	Gindai Nalah	11		0.73
	Silpi Nalah	11		0.61
Mean Melton Ratio		0.78		
KKH	Parri	17		0.86
	Goru	17		0.77

Area	Catchment name		Overall rating	Level	Melton ratio
	Jaglot Tunnel		17		2.08
	Shishkat		17		0.59
	Khyber-2		14		1.39
	Sost		17		0.43
Nagar District	Hoper Nalah		17		0.86
	Barbais Nalah		20		1.20
	Bardas Nalah		20		1.41
	Barkot Nalah		20		0.82
	Dupas Nalah		17		0.61
Ghizer Valley	Sherqilla	Sherqilla Nalah	17		0.28
		Bichar Nalah	17		0.55
	Bubur		14		0.61
	Hoper		20		0.71
	Sumal Gah		14		0.57
	Saro Gah		14		0.54
	Raushan Gah		20		1.42
	Gawote	Gawote-1	14		1.60
		Gawote-2	20		1.99
	Gupis		20		1.09
	Khalti		20		0.89
	Hilthi Nalah		17		0.49
	Langar Nalah		17		0.97
Ishkoman Valley	Ishkamitar		17		0.69
	Ishkomen Debris Flow Zone	Isk-DF1	17		1.75
		Isk-DF2	17		2.26
		Isk-DF3	17		1.59
	Immit Mass Wasting Zone	Immit-1	17		1.41
		Immit-2	17		1.95
		Immit Halbar Gol	20		0.60
Yasin Valley	Haltar Nalah		20		0.94
	Damalgan Nalah		17		0.57
	Noah Nalah		20		1.07
	Taus Chashma		17		0.81
	Asumber Nalah	Asumber Main	17		0.28
		Minerberg	17		1.16
		Brumberg	17		1.35
	Shyote Nalah		20		0.91
	Khaimith		14		0.21
	Garmish Barkulti		20		0.33
	Tarsat		20		0.92
	Umalsat		20		0.72
	Darkot Nalah		17		0.28
	Dalgiram		20		1.07
Mean Melton Ratio			0.97		

Discussion

As the 2022 rains in Pakistan were an extraordinary event and people link it with climate change so we may expect that the resultant mass movement behavior is likely to prevail in the coming years that are likely to go through a changing climate. Debris flow is the most dominant type of mass movement that the northern Pakistan is going to experience in the coming years; the phenomenon will be followed by certain types of shallow landslides including rock fall, soil slips, small rock slides (Fig. 4). Our evaluation about expected mass movement types due to climate change are in line with the findings by other researchers [*Gariano & Guzzetti, 2016; Jakob, 2021*]. Although soil slips are not recorded in our data but we think that there were some soil slips that got unnoticed due to the fact that our attention was diverted only to events that directly affected the community in some way. Similarly, our recorded event of land creep is an already existing that was accelerated due to prolonged precipitation.

The authors suggest that there would be more parameters while ranking a stream/catchment for future debris flow assessment. A detailed analysis of the catchment including its sediment supply for generating debris flow needs to be carried out for a more reliable assessment [*Bovis & Jakob, 1999; Jakob, 1996, 2021*]. The role of tectonics should also be considered while assessing the sediment supply for a particular catchment; the Hoper Nalah (Nagar District) debris flow transported huge boulders of breccia suggesting that the presence of fault line in the catchment might have facilitated the supply of material for a debris flow (Fig. 6).

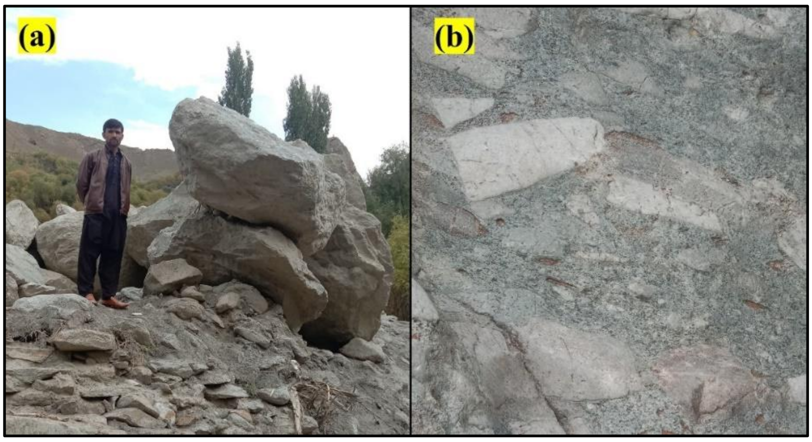

Fig. 6. Huge boulders transported by Hoper debris flow in Nagar District (a) and some of the huge size transported boulders consist of breccia (b)

Based on the currently available information two relative parameters i.e., ‘Extent of Destruction or debris transported (2022 and before)’ and event ‘frequency’ were devised in this study for carrying out a preliminary assessment. In the absence of a record of past debris flow events the actual frequency was difficult to estimate so only a frequency level (low, medium or high) was estimated through interviews by local communities and Google Earth (temporal resolution). Both the parameters are relative to the observed events; in future when more streams and catchments will be included the current rankings may be revised to fit in the system. As already discussed, the visited areas are only the selected ones based of the level of destruction and effect on the community. Debris flow in streams that lie in far flung or uninhabited areas normally go unnoticed. For example, usually the community lives along the stream bank where there passes some road so the tributaries and their watersheds along the opposite (uninhabited) bank remain unnoticed. It is quite possible that one of those tributaries my generate a debris flow of the level that it may block the main stream for a while and in turn adversely affect the downstream communities on both sides of the stream. Moreover, the current work was focused on the so called ‘high hazard’ events. The inclusion of a variety of scenarios (e.g., less disastrous catchment) will increase the authenticity of the research. A more detailed study both in terms of parameters and geographical extent is advisable for a more comprehensive assessment.

Table 4 presents a positive correlation between 'hazard level' and Melton Ration of the catchments. But Melton Ratio is not the only parameter that indicates the probability of a debris flow. The Melton Ration for Sherqilla Nalah has been calculated as 0.28 that is far low to be considered for a debris flow [*Bovis & Jakob, 1999; Jackson et al., 1987*]. But it is the same stream that responsible for a debris flow that claimed 7 lives. To identify the sub-basin that actually generated the debris flow the main basin was divided into five sub-basins i.e., A, B, C, D and E (Fig. 7); Melton Ratio, R of each sub-basin was calculated separated. R values of A, B, C, D and E were calculated as 0.34, 0.47, 0.65, 1.05 and 0.55. Initially one would expect that the sub-basins C or D with the highest values of R would be more suitable candidates but field work confirmed that the sub-basin E with the R value of 0.55 was the sub-basin that generated the debris flow. Although a reconnaissance level fieldwork was carried out but at some places the influence of readily available sediments was observed. For example, the Parri debris flow blocked about 1 km stretch of KKH by dumping about 12 feet high body of debris on August 21, 2022 at location: 35º 46΄ 07′ N, 74º 34΄ 32′ E; the traffic had to be diverted to an alternate route after a complete disruption for 4 h. A visit to its upper catchment revealed the availability of loose material on its slopes (Fig. 8).

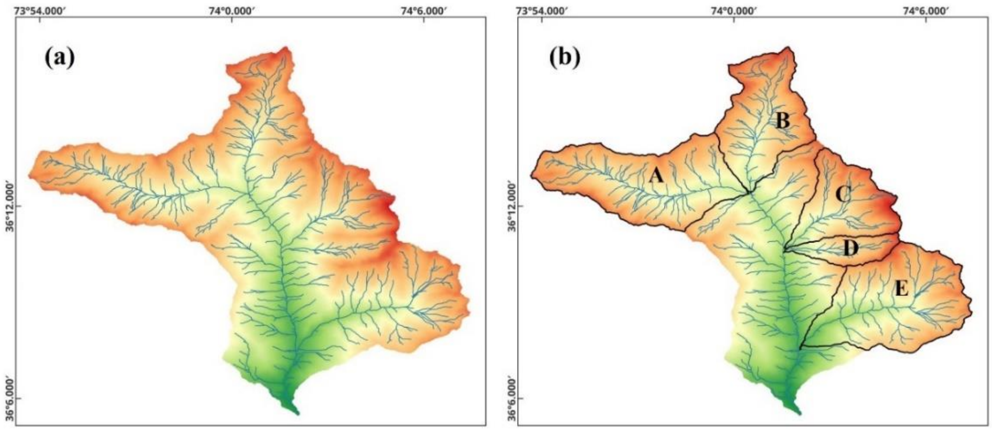

Fig. 7. The Sherqilla Nalah generated a debris flow that claimed 7 lives. Sherqilla watershed as a whole (a) watershed divided into 5 sub-basins (b)

Another important issue is the access to high resolution DEM. Henzal debris flow is produced by a small catchment in moraine deposits, blocks the road and covers the agricultural land (Fig. 9). The catchment is identified by red outline whereas the drainage network derived from ALOS PALSAR is shown in blue color. It is evident that the derived drainage network does not conform to the small catchment. So, the availability of high-resolution DEM is of prime importance for a reliable analysis of small basins.

In the recent history 2010 and 2022 were the most disastrous years in Gilgit-Baltistan in terms of mass movement particularly debris flow hazard. Interviews with the affected communities apprise that 2010 rains were more intense, less prolonged but 2022 rains were less intense more prolonged. It suggests that an increased precipitation in both ways (either in intensity or duration) have capacity to boost the debris flow phenomenon.

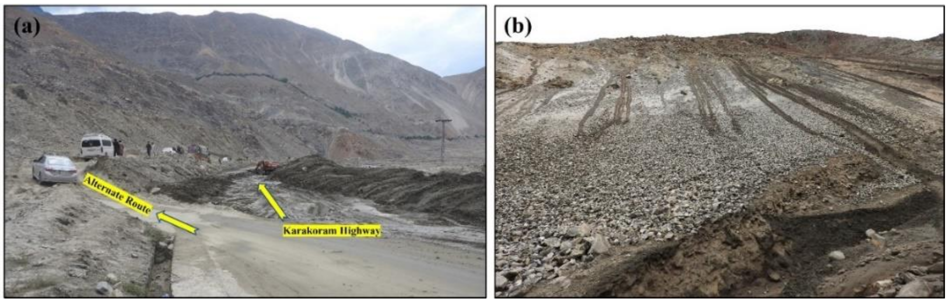

Fig. 8. Karakoram Highway blocked in August 2022 by Parri debris flow (a) and loose material along the slopes of upper reaches of the catchment, readily available for a debris flow (b)

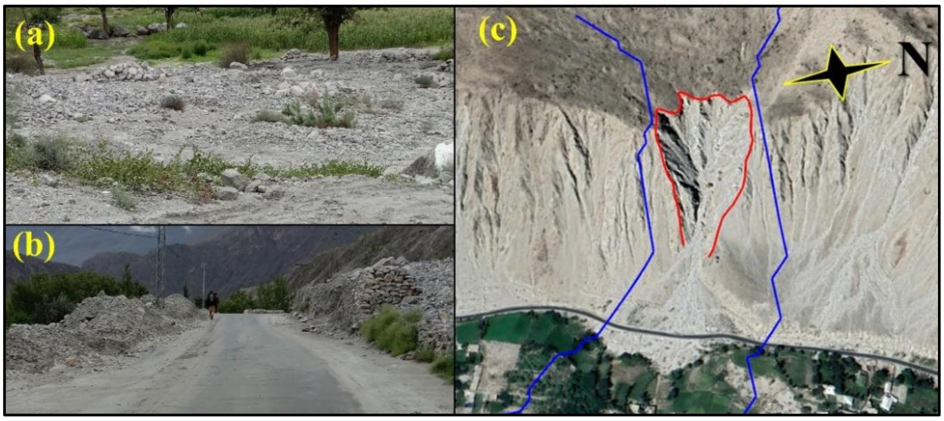

Fig. 9. Henzal debris flow covered the agricultural land (a) and blocked the road (b) and the small catchment with red outline (c), drainage network derived from DEM (in blue)

Although climate change and its adverse effects on mass movement hazards is a reality but sometimes, we blame it more than it actually deserves. Bubur debris flow in Ghizer Valley claimed 10 lives and destroyed 8 houses. As the catchment doesn't have a history of debris flows so one may very comfortably hold climate change accountable for the disaster in 2022. But anthropogenic activities got sometimes unnoticed in the hue and cry attributed to climate change (Fig. 10). The current channel width at downstream of the tragic event varies from 4–5 m; the local community has informed that it was once 10 m wide but now encroachments have restricted it to the current width. Similarly, the Khalti Nalah in Ghizer Valley was once 13 m wide but now it has been reduced to 5–6 m at places. It is very tricky to draw a clear line between the impact of climate change and that of anthropogenic activities on debris flow hazard.

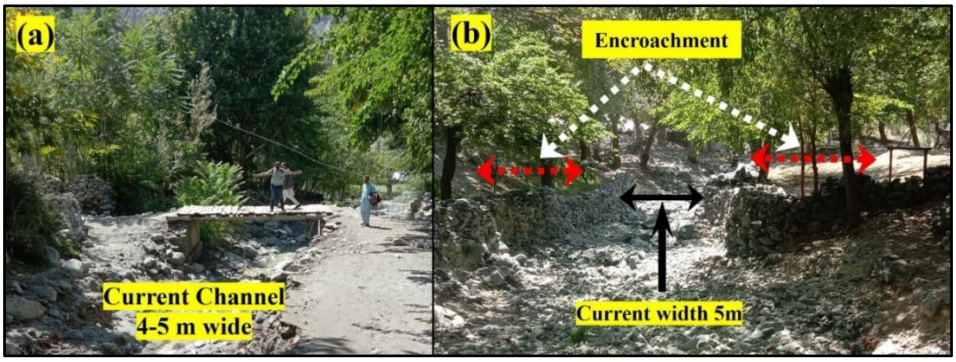

Fig. 10. Actual stream course of Bubur Nala in Ghizer Valley was once 30 ft but now reduced to about half of its original width (a). Original stream course of Khalti Nalah in Ghizer Valley now reduced to just 5–6 ft at places (b)

Conclusions

Climate change is a reality that needs to be addressed on top priority to hand over a better future to our coming generations. Projections show that the temperature increase in Pakistan would be more than the global average; rainfall duration is also expected to increase while some areas will experience an increase in intensity. Experience of 2010 and 2022 events suggest that increase in rainfall (either in intensity or duration) would trigger more mass movement events. Although it is not simple to assess the impact of changing climate on mass movement hazards but it is highly probable that more landslides will be triggered specially the shallow landslides including debris flows, rock falls, soil slips, small rock slides. Although Melton Ration gives a good first estimation about the streams capable of generating debris flow but a lot of other parameters are also important, they need to be addressed as well. A lot of work needs to be done for a reliable hazard assessment in the country. In fact, the individual catchments need to be studied in more detail on sub-basin level to identify the problematic sub-basins.

Acknowledgements

The fieldwork for current study was financed by Government of Pakistan through its Public Sector Development Program “Pakistan National Research Program on Geological Hazards (Earthquakes and Landslides), Data Acquisition along Active Faults and Identification of Potential Landslide Hotspot Zones”.

References

AAAS. (2014). What We Know: The Reality, Risks, and Response To Climate Change.

Ahmed, M. F., Rogers, J. D., & Ismail, E. H. (2015). Historic Landslide Dams along the Upper Indus River, Northern Pakistan. Natural Hazards Review, 16(3), 04014029. https://doi.org/10.1061/(asce)nh.1527-6996.0000165

Akhtar, S. S., Awan, A. A., & Sadiq, S. (2017). Seismotectonic and Anthropogenic Causes for Potential Hazard of Slope Failure in Miachar Village, District Hunza Nagar, Gilgit-Baltistan, Pakistan. Geological Survey of Pakistan, Information Release No. 1020.

Ashraf, A., Roohi, R., Naz, R., & Mustafa, N. (2014). Monitoring cryosphere and associated flood hazards in high mountain ranges of Pakistan using remote sensing technique. Natural Hazards, 73(2), 933–949. https://doi.org/10.1007/s11069-014-1126-3

Basharat, M., Rohn, J., Baig, M. S., Khan, M. R., & Schleier, M. (2014). Large scale mass movements triggered by the Kashmir earthquake 2005, Pakistan. Journal of Mountain Science, 11(1), 19–30. https://doi.org/10.1007/s11629-012-2629-6

Berkeley Earth. (2024). Global Temperature Report for 2023. https://berkeleyearth.org/global-temperature-report-for-2023/

Bovis, M. J., & Jakob, M. (1999). The role of debris supply conditions in predicting debris flow activity. Earth Surface Processes and Landforms, 24(11), 1039–1054. https://doi.org/10.1002/(SICI)1096-9837(199910)24:11<1039::AID-ESP29>3.0.CO;2-U

Climate Risk Country Profile: Pakistan. (2021). The World Bank Group and the Asian Development Bank.

Delbeke, J., & Vis, P. (Eds.). (2019). Towards a Climate-Neutral Europe. Routledge. https://doi.org/10.4324/9789276082569

Farah, A., Lawrence, R. D., & DeJong, K. A. (1984). An overview of the tectonics of Pakistan. In B. U. Haq & J. D. Milliman (Eds.), Marine geology and oceanography of Arabian Sea and coastal Pakistan. Van Nostrand Reinhold/Scientific and Academic Editions.

Gariano, S. L., & Guzzetti, F. (2016). Landslides in a changing climate. Earth-Science Reviews, 162, 227–252. https://doi.org/10.1016/j.earscirev.2016.08.011

Gilchrist, A. R., Summerfield, M., & Cockburn, H. A. P. (1994). Landscape dissection, isostatic uplift and the morphologic development of orogens. Geology, 22, 963–966.

Hewitt, K. (1998). Catastrophic landslides and their effects on the Upper Indus streams, Karakoram Himalaya, northern Pakistan. Geomorphology, 26(1–3), 47–80. https://doi.org/10.1016/S0169-555X(98)00051-8

Hewitt, K. (1999). Quaternary moraines vs catastrophic rock avalanches in the Karakoram Himalaya, Northern Pakistan. Quaternary Research, 51(3), 220–237. https://doi.org/10.1006/qres.1999.2033

Hewitt, K. (2006). Disturbance regime landscapes: Mountain drainage systems interrupted by large rockslides. Progress in Physical Geography, 30(3), 365–393. https://doi.org/10.1191/0309133306pp486ra

Hussain, S. H., & Awan, A. A. (2009). Causative Mechanisms of Terrain Movement in Hunza Valley. Geological Survey of Pakistan, Information Release No. 925.

IPCC. (2023). Summary for Policymakers. In Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)] (pp. 1–34). IPCC, Geneva, Switzerland. https://doi.org/doi: 10.59327/IPCC/AR6-9789291691647.001

Jackson, L. E., Kostaschuk, R. A., & MacDonald, G. M. (1987). Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. GSA Reviews in Engineering Geology, 7, 115–124. https://doi.org/10.1130/REG7-p115

Jakob, M. (1996). Morphometric and Geotechnical Controls of Debris Flow Frequency and Magnitude in Southwestern British Columbia (Issue October). University of British Columbia.

Jakob, M. (2021). Landslides in a changing climate. In T. Davies, N. Rosser, & J. F. Shroder (Eds.), Landslide Hazards, Risks, and Disasters (Second, Vol. 162, pp. 505–579). Elsevierice j. https://doi.org/10.1016/B978-0-12-818464-6.00003-2

Khan, S., Javed, Hussain, Z., Wahid, A., Ranjha, Naveed, A., & Hasan, Ul, M. (2020). Climate of Gilgit Baltistan Province Pakistan. Int. J. Econ. Environ. Geol., 11(January).

Korup, O. (2004). Landslide-induced river channel avulsions in mountain catchments of southwest New Zealand. Geomorphology, 63(1–2), 57–80. https://doi.org/10.1016/j.geomorph.2004.03.005

Korup, O. (2005). Large landslides and their effect on sediment flux in South Westland, New Zealand. Earth Surface Processes and Landforms, 30(3), 305–323. https://doi.org/10.1002/esp.1143

Latif, M., Akhtar, S. S., Sadiq, S., & Khan, M. Q. (2015). Preliminary Report on 2005 Kashmir Earthquake Related Mass Movement Hazards in Neelum Valley, Azad Jammu & Kashmir. Geological Survey of Pakistan, Information Release No. 968.

Latif, M., Akhtar, S. S., Sadiq, S., & Shah, M. N. (2013). A Quick Report on Slope Failure in Shulja, Dilkushan and Daeen Areas of Chatorkhand, District Ghizer, Gilgit-Baltistan, Pakistan. Geological Survey of Pakistan, Information Release No. 937.

Latif, M., Hussain, S. H., & Sadiq, S. (2016). Study of Hazardous Areas of Hunza-Nagar District, Gilgit-Baltistan, Pakistan. Geological Survey of Pakistan, Information Release No. 967.

Melton, M. A. (1965). The Geomorphic and Paleoclimatic Significance of Alluvial Deposits in Southern Arizona. The Journal of Geology, 73(1), 1–38.

Ministry of Planning Development & Special Initiatives. (2022). Pakistan Floods 2022 – Post-Disaster Needs Assessment: Main Report.

Myers, K. F., Doran, P. T., Cook, J., Kotcher, J. E., & Myers, T. A. (2021). Consensus revisited: quantifying scientific agreement on climate change and climate expertise among Earth scientists 10 years later. Environmental Research Letters, 16(10), 104030. https://doi.org/10.1088/1748-9326/ac2774

Nash, D. F. T., Brunsden, D. K., Hughes, R. E., Jones, D. K. C., & Whalley, B. F. (1985). A Catastrophic Debris Flow near Gupis, Northern Areas, Pakistan. 111th International Conference on Soil Mechanics and Foundation Engineering (San Francisco).

Nyaupane, G. P., & Chhetri, N. (2009). Vulnerability to Climate Change of Nature-Based Tourism in the Nepalese Himalayas. Tourism Geographies, 11(1), 95–119. https://doi.org/10.1080/14616680802643359

Owen, L. A., Sharma, M. C., & Bigwood, R. (1996). Landscape modification and geomorphological consequences of the 20th October 1991 earthquake and the July-August 1992 monsoon in the Garhwal Himalaya. Zeitschrift Fur Geomorphologie, Supplementband, 103(January 2018), 359–372.

Palmer, J. (2020). A Slippery Slope: Could Climate Change Lead to More Landslides? Eos, 101(August). https://doi.org/10.1029/2020EO151418

Petley, D. (2012). Global patterns of loss of life from landslides. Geology, 40(10), 927–930. https://doi.org/10.1130/G33217.1

Pierrehumbert, R. T. (2006). Climate Change: A Catastrophe in Slow Motion. Chicago Journal of International Law, 6(2), 573–596.

PMD. (2022). Pakistan Meteorological Department – Pakistan Monsoon 2022 Rainfall Report.

Rajbhandari, R., Shrestha, A. B., Kulkarni, A., Patwardhan, S. K., & Bajracharya, S. R. (2015). Projected changes in climate over the Indus river basin using a high resolution regional climate model (PRECIS). Climate Dynamics, 44(1–2), 339–357. https://doi.org/10.1007/s00382-014-2183-8

Roering, J. J., Kirchner, J. W., & Dietrich, W. E. (2005). Characterizing structural and lithologic controls on deep-seated landsliding: Implications for topographic relief and landscape evolution in the Oregon Coast Range, USA. Bulletin of the Geological Society of America, 117(5–6), 654–668. https://doi.org/10.1130/B25567.1

Sadiq, S., Latif, M., Shah, M. N., & Akhtar, S. S. (2012). Gyari Avalanche Mapping, Siachen Glacier Region, Gilgit-Baltistan. Geological Survey of Pakistan Information Release No. 938.

Sadiq, S., & Momose, Y. (2017). Monitoring of geohazards related to 2005 Kashmir Earthquake in Muzaffarabd area during monsoon 2006. Geological Survey of Pakistan, Information Release No. 1012.

Sadiq, S., Muhammad, U., & Fuchs, M. (2021). Investigation of landslides with natural lineaments derived from integrated manual and automatic techniques applied on geospatial data. Natural Hazards. https://doi.org/10.1007/s11069-021-05028-6

Sadiq, S., & Shah, M. N. (2016a). Geohazard Assessment of Selected Sites in Gilgit District, Gilgit-Baltistan, Pakistan. Geological Survey of Pakistan, Information Release No. 1024.

Sadiq, S., & Shah, M. N. (2016b). Geohazard Assessment of Vulnerable Localities in Ghizer District, Gilgit-Baltistan, Pakistan. Geological Survey of Pakistan, Information Release No. 1023.

Sato, H. P., Hasegawa, H., Fujiwara, S., Tobita, M., Koarai, M., Une, H., & Iwahashi, J. (2007). Interpretation of landslide distribution triggered by the 2005 Northern Pakistan earthquake using SPOT 5 imagery. Landslides, 4(2), 113–122. https://doi.org/10.1007/s10346-006-0069-5

Shroder, J. F., & Bishop, M. P. (1998). Mass movement in the Himalaya: New insights and research directions. Geomorphology, 26(1–3), 13–35. https://doi.org/10.1016/S0169-555X(98)00049-X

Torizin, J., Wang, L. chao, Fuchs, M., Tong, B., Balzer, D., Wan, L. qin, Kuhn, D., Li, A., & Chen, L. (2018). Statistical landslide susceptibility assessment in a dynamic environment: A case study for Lanzhou City, Gansu Province, NW China. Journal of Mountain Science, 15(6), 1299–1318. https://doi.org/10.1007/s11629-017-4717-0

UNDP. (2017). The Vulnerability of Pakistan’s Water Sector to the Impacts of Climate Change: Identification of Gaps and Recommendations for Action.

UNEP. (2019). United Nations Environment Programme – Emissions Gap Report 2019. UNEP, Nairobi.