Comprehensive analysis of surface characteristics of debris flow fans in Gilgit-Baltistan and Chitral regions of Pakistan using remote sensing

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Abstract. The northern part of Pakistan has faced severe climate change impacts during the last few decades. During these years there were huge debris flow and flash floods events which caused huge number of casualties and million dollars' economic losses. Debris flow (DF) and floods represent one of the major natural hazards that impact infrastructure, transport, economic losses, human lives, and regional economy. With continuous advancement in Remote Sensing (RS) field particularly in spatial and temporal resolution of image, its application in geosciences has become more widespread. Therefore, in this study, the potential of Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) and Sentinel-2 image collection was explored to perform analysis of characteristics of 5,535 DF fans over 5 districts of Gilgit-Baltistan and Chitral (GBC). The DF fans data was prepared by Aga Khan Agency for Habitat, Pakistan (AKAH, P) and retrieved from their database with approximate area of 309.2 km^2. Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) from 2000-2019 was evaluated to find connection between environmental parameters and debris flow activity. Different GIS platforms were used to analyze different topographic and morphometric parameters viz slope, aspect, elevation, Topographic Roughness Index (TRI), Plan curvature, Profile curvature, Total curvature, Topographic Wetness Index (TWI), Terrain Ruggedness Index, Texture and Topographic Position Index (TPI). Additionally, four environmental parameters, mean annual precipitation, land cover and Normalized Difference Vegetation Index (NDVI) were also analyzed. Moreover, all the parameters were evaluated against the debris flow hazard intensity classes (High, Medium, Low).

Key words: *debris flow fans, remote sensing, geomorphological characteristics, Gilgit-Baltistan and Chitral*

Cite this article: Amin G., Bano D., Wali S., Shah S. Comprehensive analysis of surface characteristics of debris flow fans in Gilgit-Baltistan and Chitral regions of Pakistan using remote sensing. In: Chernomorets S.S., Viskhadzhieva K.S. (eds.) Debris Flows: Disasters, Risk, Forecast, Protection. Proceedings of the 6th International Conference (Dushanbe–Khorog, Tajikistan). Volume 1. Dushanbe: "Promotion" LLC, 2020, p. 122–133.

Комплексный анализ геоморфологических характеристик селевых конусов выноса в Гилгит-Балтистане и Читрале (Пакистан) с использованием данных дистанционного зондирования

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Аннотация. В последние десятилетия северной части Пакистана пришлось столкнуться с серьезными последствиями современных быстрых изменений климата. За этот период произошли катастрофические селевые потоки и ливневые паводки, которые привели к большому числу жертв среди населения и значительным экономическим потерям, которые оцениваются в миллионы долларов

США. Селевые потоки и ливневые паводки представляют собой одни из основных опасных природных процессов, которые угрожают инфраструктуре, транспорту, населению и региональной экономике Пакистана. В связи с постоянным прогрессом в области дистанционного зондирования, особенно в сфере, касающейся пространственно-временного разрешения снимков, применение его данных в геонауках получает все более широкое распространение. Поэтому в данном исследовании был рассмотрен потенциал использования данных ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) и космических снимков со спутника Sentinel-2 для анализа характеристик 5535 селевых конусов выноса в 5 районах Гилгит-Балтистана и Читрала. Данные о селевых конусах выноса были ранее подготовлены филиалом Агентства Ага Хана по Хабитат в Пакистане и собраны в единую базу данных. Для представленного исследования из нее были взяты данные на участок общей площадью примерно 309,2 км^2. Также использовались метеоданные CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) за 2000-2019 гг. с целью выявления связи между параметрами окружающей среды и активностью селевых потоков. Для анализа морфометрических параметров, таких как крутизна склонов, их экспозиция, высота, индекс шероховатости, плановая кривизна, кривизна профиля, общая кривизна, индекс топографической влажности, индекс расчлененности рельефа, текстура и индекс топографического положения, использовались различные геоинформационные программы. Кроме того, были проанализированы три параметра окружающей среды (среднегодовое количество осадков, почвенно-растительный покров и NDVI (нормализованный вегетационный индекс). Все параметры были оценены по классам селевой активности (высокий, средний, низкий).

Ключевые слова: *селевые конусы выноса, дистанционное зондирование, геоморфологические характеристики, Гилгит-Балтистан и Читрал*

Ссылка для цитирования: Амин Г., Бано Д., Вали Ш., Шах С. Комплексный анализ геоморфологических характеристик селевых конусов выноса в Гилгит-Балтистане и Читрале (Пакистан) с использованием данных дистанционного зондирования. В сб.: Селевые потоки: катастрофы, риск, прогноз, защита. Труды 6-й Международной конференции (Душанбе–Хорог, Таджикистан). Том 1. – Отв. ред. С.С. Черноморец, К.С. Висхаджиева. – Душанбе: ООО «Промоушн», 2020, с. 122–133.

Introduction

The mountain landscape with steep slopes and fragile geology experiences mass-wasting phenomena termed as Debris Flow. Debris Flow (DF) refers to debris allied flows and floods under gravity. This process is usually initiated at uninhabited and elevated altitudes and gets deposited in lower urbanized zones. Extreme velocity, longer runout distances and shear force places DF amongst the most hazardous mass movements [*Hürlimann et al., 2019*]. Tremendous force is applied on the obstacles in the path and depositional area by DF having great velocity and mass. The land in the lower mountainous regions is usually habitable or it supports development works [*Khan et al., 2013*].

Debris flow have always been of prime concern in the mountainous areas because of its ability to disrupt lives and damage infra-structure and environment at large. The cryosphere is prominently impacted by climatic warming which directly influences multiple phenomena in terms of frequency and magnitude of DF, glacial lake outburst floods (GLOFs), snow avalanches and landslides *[Šilhán & Tichavský, 2017; Tomczyk & Ewertowski, 2017; Zaginaev et al., 2019*]. Also, the geomorphological processes have been impacted by melting glaciers thus resulting in increased debris falls, slides and flows, down wasting and back wasting of melting of dead ice. However, based on formation, fans or landforms are classified into two categories alluvial and colluvial [*Tomczyk & Ewertowski, 2017]*. As complex network of tributaries drains the valley slopes, the tributary junctions are sites of alluvial fans, debris cones and debris fans due to deposition of sediments. Moreover, the terraces of the valley flanks formed by deposits of glaciofluvial, morainic, fluvial and lacustrine origin can be seen with present-day fans rest upon relict of these [*Kamp Jr et al., 2004*].

The northern Pakistan straddles the Hindukush–Karakoram–Himalaya (HKH) Range neighboring with China towards east and northeast, India to its south & southeast and Afghanistan towards north. Chitral district (~14751 km^2) in the province of Khyber Pakhtunkhwa, and four districts from Gilgit-Baltistan viz Ghizer (~12043 km^2), Gilgit (~4009 km^2), Hunza (~11343 km^2) and Nagar (~2993 km^2) were selected as study area (Fig. 1). The study area is drained by famous Indus and Chitral river (also called Kabul River in Afghanistan). The flank of these rivers and other small tributaries provide livelihood opportunities and support human settlement, croplands, and small orchards. These areas are famous for large glacier bodies which are associated with various natural hazards. Valley facing slopes are most common geomorphic feature of northern areas, mostly are associated with flat floodplains formed relatively by merged high relief mountains. The modification of surface and formation of these landforms is frequent in the region due to meteorological, anthropogenic, geological structures and hydrological conditions [*Khan et al., 2013*]. This increased frequency has led to the formation of numerous distinct DF fans earlier and in recent times. Thus, it is of prime importance to conduct extensive research on DF fans for providing basic information of the process, which will assist in understanding and classification of hazards associated with it. The dominant wet season in the Gilgit-Baltistan and Chitral (GBC) extends from December to May, wettest being March and April. From December to mid-March, precipitation falls in the form of snow and afterwards rainfall dominates, although some spells of snowfall are recorded until early May usually up to 3,000 m asl elevation. Precipitation trend (annual mean) of study area from year 2000-2019 based on CHIRPS gridded data is presented in Fig. 2.

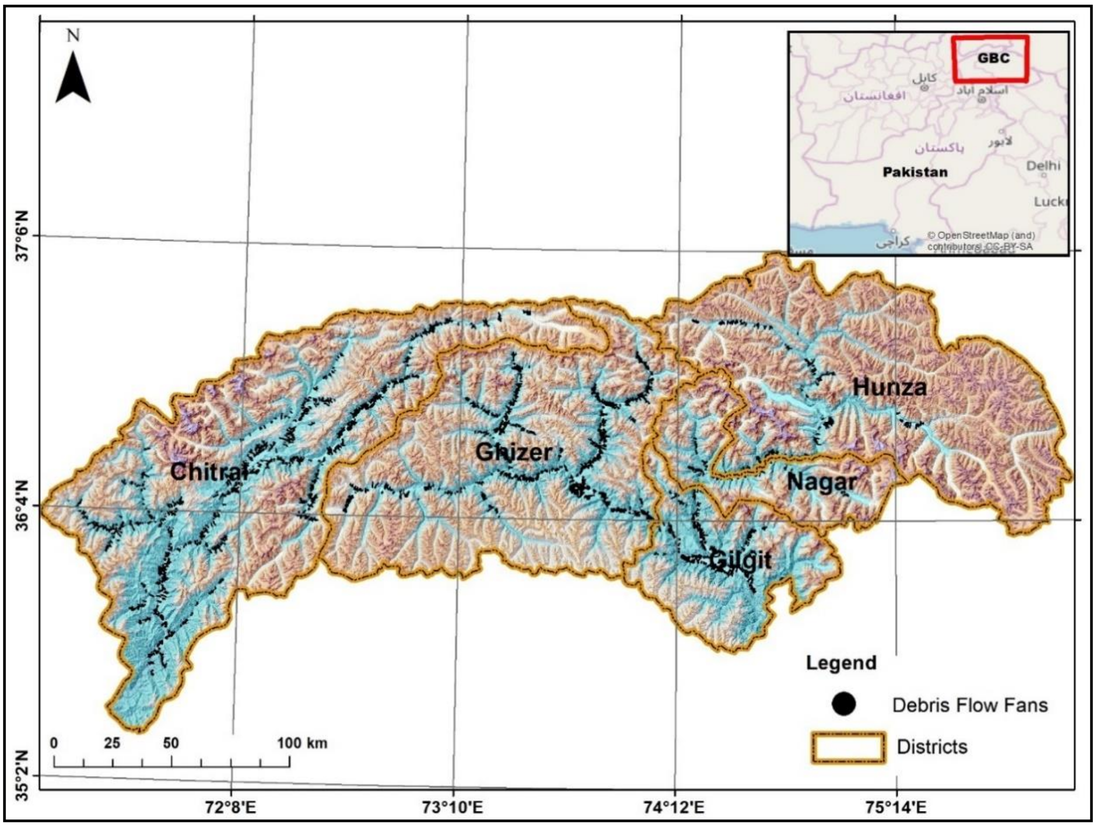

Fig. 1. Relief map of study area with spatial distribution of DF fans

DF fans hazard assessment is vital to manage danger and minimize damages it can cause, for which understanding of the surface morphology is of prime importance. The DF associated risk can be identified and assessed employing remote sensing technology on regional and local level [*Kritikos & Davies, 2015; Shrestha et al., 2016; N. Zhang & Matsushima, 2018; Ali et* *al., 2019; Jamil et al., 2019*]. On regional level preliminary analysis regarding the characteristics of debris flow can be done. To achieve the objectives, different morphometric parameters viz Slope, Aspect, Elevation, Topographic roughness index (TRI), Plan curvature, Profile curvature, Total curvature, Topographic Wetness Index (TWI), Terrain Ruggedness Index, Texture and Topographic Position Index (TPI) were investigated against the DF hazard intensity. Moreover, environmental parameters such as mean annual precipitation, land cover and Normalized Difference Vegetation Index (NDVI) over the area of interest were evaluated against the DF hazard intensity (High, Medium and Low).

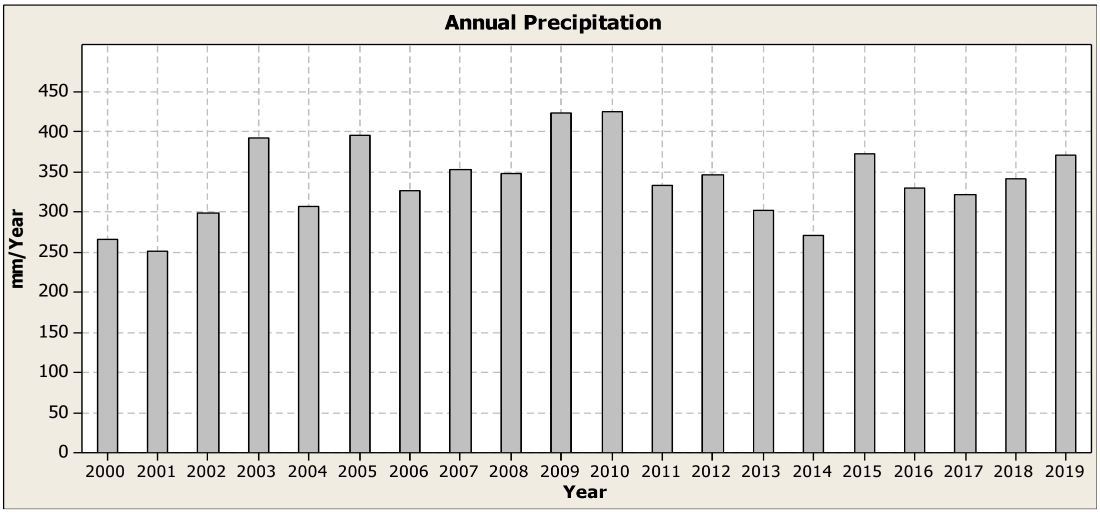

Fig. 2. Mean annual precipitation over selected districts

This study aims in 1) providing surface morphology of DF fans in northern Pakistan; 2) identification of various parameters influencing the DF fans on regional level; 3) assessment of environmental and morphological parameters in accordance with DF hazard intensity.

Brief review of the problem

In past few and limited geohazards studies were performed in norther areas of Pakistan due to limited resources and tough conditions. Majority of these studies were related to hazards associated with glaciers and outburst floods [*Jamil et al., 2019; Shah et al., 2019*]. Various researchers have found explanations of Quaternary sediments in the region [*Haserodt, 1968; Buchroithner, 1980*]. In the Eastern Hindu Kush region DF deposits were described by [*Wasson, 1978*] including an eye-witness account of a DF event on August 14, 1975 at Reshun, Chitral. A recent study was performed on landslide inventory and susceptibility mapping in Hunza-Nagar districts of Gilgit-Baltistan (GB) [*Bacha et al., 2018*] and has discussed major causative factors triggering landslides including debris flows in mountainous areas. Another study along the International Karakoram Highway was performed by Yang, Zhu, Zou, & Liao (2011) using fuzzy evaluation method to investigate glacier induced debris flows. The debris flows in the region are triggered due to unique geology, geomorphology and landform conditions characterized by steep mountain slopes, as mentioned in various studies [*Bacha et al., 2018; Ali et al., 2019; Y. Zhang et al., 2019*].

After brief literature review of the study area, it was noticed that majority of research was centered around susceptibility mapping of landslides using various models as discussed above. Moreover, no previous study described debris flow fans on large regional scale making the current study first ever in the region describing the characteristics of debris flow fans, various geophysical factors and its exposure.

Method and data

We derived topographic and geomorphological metrics from Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) with 30m resolution. The environmental parameters were derived from cloud free Sentinel-2 satellite image composite (May 1 – September 30, 2019) having resolution of 10 m, and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) rainfall dataset which incorporates 0.05° resolution satellite derived rainfall with in-situ station data to create gridded rainfall time series for trend analysis and environmental monitoring [*Funk, 2015*]. The DF fans were retrieved from Hazard Vulnerabilities and Risk Assessment (HVRA) database maintained by AKAH Pakistan. HVRA starts with development of community level hazard inventory and historic profile of hazards and their impact, development of baseline data on most hazardous sites for further investigation. After field investigations by AKAHs technical teams, the data is digitally presented using GIS platforms. Using the collected data, the DF fans were categorized into hazard class based on DF hazard return period and intensity data collected from communities using questionnaire. Here the return period is the frequency of DF with reference to time i.e. < 10 years, > 30 years and 10 - 30 years, while intensity corresponds to high, medium and low. Finally, based on return period and intensity all the DF fans were categorized into three hazard classes which are High, Medium and Low.

Environmental Parameters

Sentinel-2 Surface reflectance product (Band: B2-B8, B11 and B12) was retrieved from Google Earth Engine (GEE) for image classification in the study area for year 2019 (1st May-30th September). The image classification over the study region was used to extract the surface condition of DF fans. NDVI was calculated using band B4 and B8 to distinguish the surface of DF fans into barren land and vegetation using the historical satellite data of S-2 from 2014-2019 in GEE platform. The reason to calculate this parameter was to recognize any active DF fan and to investigate the intensity and return period. The greater the NDVI value the lower risk of DF, and vice versa [*Y. Zhang et al., 2019*]. Additionally, annual mean precipitation from CHIRPS (2000-2019) was used to analyze the precipitation trend and amount of rain DF fans received.

Geomorphic Parameters

The different morphometric including topographic parameters were measured such as slope, aspect and elevation in ArcGIS 10.7. While, the surface curvature (plan curvature, profile curvature and total curvature) were derived too using DEM in ArcGIS. It should be noted that slope and curvature are the first and second-order local derivatives of the topographic surface, respectively [*Deng et al., 2008*].

In addition, the topographic wetness index, terrain ruggedness index, texture and topographic position index (TPI) were derived using SAGA platform. Here the topographic roughness index (TRI), terrain ruggedness Index which is defined as the mean difference between a central pixel and its surrounding cells indicates soil saturation and water content it can retain [*Lindsay et al., 2019; Nicu, 2018*]. Moreover, the topography of mountainous area can vary from smooth to irregular texture. Roughness metrics that characterize surface complexity can be analyzed using the topographic roughness index and texture [*Lindsay et al., 2019*].Therefore, terrain roughness index parameter was used to differentiate the local land features on the scale of the microrelief. The TPI quantifies terrain roughness by subtracting the mean elevation of a defined neighborhood from each cell [*Deng et al., 2008; Elkadiri et al., 2014; Walk et al., 2019*]. Depending on the scale of the neighborhood, the TPI enables discrimination of local differences in elevation within a landform [*Walk et al., 2019*]. The TRI has been calculated in ArcGIS using a smoothed DEM of 10 × 10 pixel based on relative topographic position index which reflect terrain ruggedness matrix and local elevation index [*Lindsay et al., 2019; Sahani, 2019*].

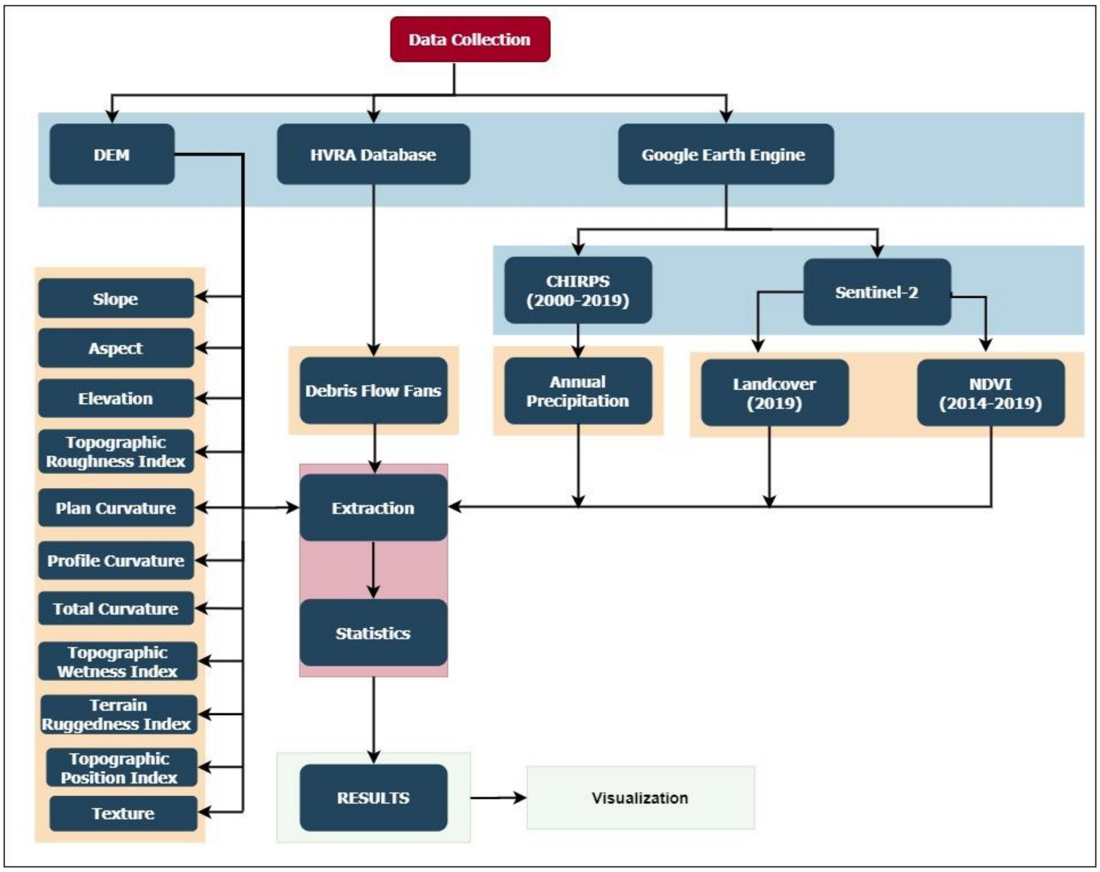

Fig. 3. Flowchart of the methodology for analysis of characteristics of DF fans in GBC

A total of 5,535 DF fans of various size were acquired from AKAHs HVRA database prepared after extensive field investigation. A detailed description of various parameters used in this research are presented in Table 1.

Table 1. Features, types & units, source and processing platform of calculated geomorphic properties of DF fans.

Features	Type and unit	Data source	Processing
Slope	Continuous (°)	DEM	Arc GIS
Aspect	Continuous (°)	DEM	Arc GIS
Elevation	Continuous (m)	DEM	Arc GIS
Plan curvature	Quantitative	DEM	ARC GIS
Profile curvature	Quantitative	DEM	ARC GIS
Total curvature	Quantitative	DEM	ARC GIS
Topographic Roughness Index	Quantitative	DEM	Arc GIS
Topographic Wetness Index	Quantitative	DEM	SAGA
Terrain Ruggedness Index	Quantitative	DEM	SAGA
Topographic Position Index	Quantitative	DEM	SAGA
Texture	Quantitative	DEM	SAGA
NDVI	Quantitative	Sentinel-2	GEE
Land cover	Nominal	Sentinel-2	GEE
Mean annual precipitation	mm/year	CHIRPS	GEE

Analysis

A total of 5,535 DF fans over 5 districts of GBC from AKAH database were retrieved database which covers an approximate area of 309.2 km^2, where the spatial distribution is shown in Fig. 1.

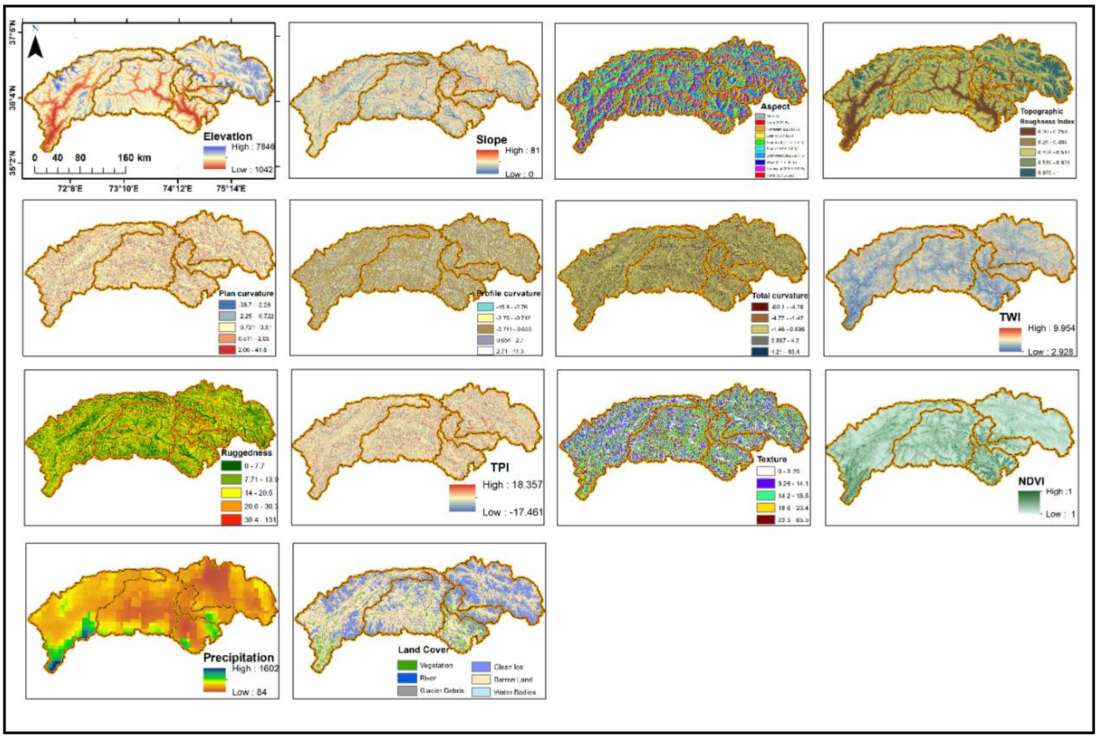

Fig. 4. Map panel showing different parameters calculated in study area for DF fan analysis

Characteristics of debris flow fans

Based on the comprehensive RS interpretation of the DF fans in the study area, different morphological and environmental characteristics of the DF fan are calculated and analyzed (Fig. 4 & Table 2). The results showed that DF fans in the study area are mostly located at mean elevation of 2278m with mean slope of 15.5°. The relatively high slope angle (51.4° maximum) indicates that deposition of sediments from the upper streams dominate the constructing processes of the DF fans and other landforms.

Curvature of slope is responsible for controlling the flow of water during rainfall. Curvature was measured based on planar profiles. Concave slopes with high negative values tend to retain water for a longer period after rainfall and this causes loosening of top layer soil [*Negi et al., 2020*]. The mean NDVI in the region indicated that the DF fans comprised of intermediate green vegetation which include grasses and wastelands [*Zeng et al., 2020*], which is in good agreement with field observations.

Characteristics of debris flow hazard intensity

The analysis of DF hazard in GBC identified 1581 DF fans with high intensity and high frequency making them a potential hazard in the region. However, the most predominant class is medium intensity with generational return period with total of 1984 counts. Also, the results showed that DF are recursive geohazards in the study area (Table 3).

Table 2. Statistics of different parameters extracted over DF fans

Parameters	**Mean**	**StDev**	**Minimum**	**Maximum**	**Median**
Slope	15.447	8.1	1.288	51.467	13.689
Aspect	180.41	79.82	3.15	357.63	177.92
Elevation	2278	542.5	1068	3733.7	2301.5
Plan curvature	-0.07287	0.24146	-2.4157	1.88244	-0.03605
Profile curvature	0.13195	0.3012	-4.58525	5.2989	0.08347
Total curvature	-0.20498	0.46557	-6.21894	6.46769	-0.12957
Topographic Roughness Index	0.18539	0.08104	0.00453	0.40124	0.18854
Topographic Wetness Index	5.2138	0.6203	3.4761	7.5399	5.2087
Terrain Ruggedness Index	6.0094	3.4284	0.7431	25.8225	5.1652
Topographic Position Index	-0.2734	0.33655	-3.25954	1.43234	-0.20623
Texture	9.6009	4.3993	0.8469	27.2214	8.9882
NDVI	0.40019	0.2095	-0.05383	0.90239	0.40075
Mean annual precipitation	304.93	116.64	98.83	868.61	304.82

Table 3. Characteristics & frequency matrix of DF fans in the study area

	Return Period				
Intensity		**Frequent (< 10 years)**	**Generational (10-30 years)**	**Rare (> 30 years)**	**Grand Total**
	High	1581	93	0	**1674**
	Low	0	79	1716	**1795**
	Medium	39	1984	43	**2066**
	Grand Total	**1620**	**2156**	**1759**	**5535**

Fig. 5 shows the visual impression of selected geomorphological and environmental parameters evaluated against the DF hazard intensity. The histogram of profile curvature indicates that hazard intensity classes have linear slope. The mean value of high DF intensity class indicates less planner surface as compare to other hazard intensity classes (Fig. 5a). The results show that all three DF hazard classes have negative value for total curvature. While, the high hazard class has lower values indicating the presence of DF fans in channels and valleys (Fig. 5b). As the plan curvature illustrates the curvature in the horizontal plane, the positive value indicates concave contour while negative value indicates convex contour across the surface. The results show that the DF fans in our study area have negative plan curvature, which make it clear that DF fans are found across the valleys not along the ridges (Fig. 5c). Moreover, the profile of high hazard class shows that high hazard class is least concave as compare to other hazard classes (Fig. 5a). The slope angle of DF fans show that high DF intensity class has larger value of slope as compare to others which slope over 18° are potentially susceptible to DF hazards (Fig. 5d). While the mean aspect angle for the DF fans shows that they have south facing angle (174°-180°), which indicates that south facing slopes are more prone to DF (Fig. 5e). The TPI values for DF fans depict very low value indicating the position of DF fans in valleys with lower slope angle (Fig. 5f).

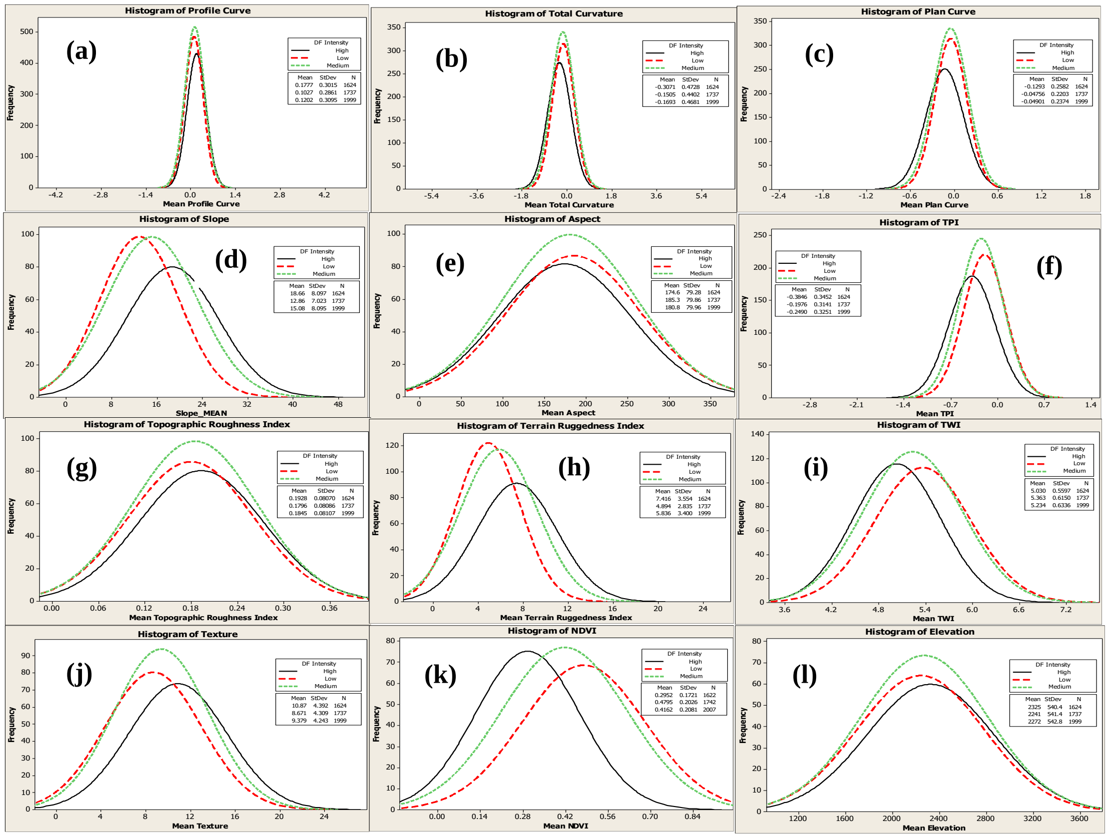

Fig. 5. Histogram (normal curve) of selected geomorphological and environmental parameters evaluated against the DF Hazard Intensity. where, (a) Profile curvature, (b) Total curvature, (c) plan curvature, (d) Slope, (e) Aspect, (f) TPI, (g)Topographic roughness index, (h) Terrain ruggedness Index, (i) TWI, (j) Texture (k) NDVI and (l) Elevation.

Topographic roughness index and terrain ruggedness index both describes the texture of area (Fig. 5g). Our analysis shows that the high hazard class has higher values for both roughness and ruggedness indexes which validate our results that high DF intensity class has coarse surface as compare to other (Fig. 5g and h). The high values of TWI represent wet areas and low values dry areas. The results showed that DF fans with high intensity are dry as compare to their mean TWI values (Fig. 5i). While the texture of DF fans indicates high DF hazard class has higher value of texture as compared to other making it clear that high DF intensity fans have coarse surface, indicating the presence of larger boulders and rocks (Fig. 5j). The observed NDVI value for DF fans depicts that the high intensity hazard class has lower value (0.29) compared with the other DF intensity classes (Fig. 5k). This indicates that there is sparse vegetation on high DF intensity fans. The reason behind this is the surface of DF fans is barren, rocky, coarse and with irregular gullies making it difficult for vegetation to grow or also indicating that the return period is high. The elevation for hazard intensity classes remains between 2272 to 2241 (Fig. 5l). The histogram for elevation depicts that high hazard class DF fans are located at higher elevations, while low hazard class DF fans at lower elevation as compare to other. The medium class DF fans are placed in between the high and low elevation.

To understand the impact of precipitation over DF fans it was observed that the annual mean precipitation was approximately 304.9 mm/year (Fig. 6). Variations in precipitation pattern can damage vegetation in climatic conditions of study area [*Rasul et al., 2012*]. However, the observed rain is enough for sustaining vegetation and making the barren land greener. In general, it is said that, places which gain more rainfall have high vegetation index and vice versa. However, it is very eminent that in most of the cases the DF can be triggered due to excessive rainfall [*Wu et al., 2020; Y. Zhang et al., 2019*], ultimately damaging the vegetation and other resources.

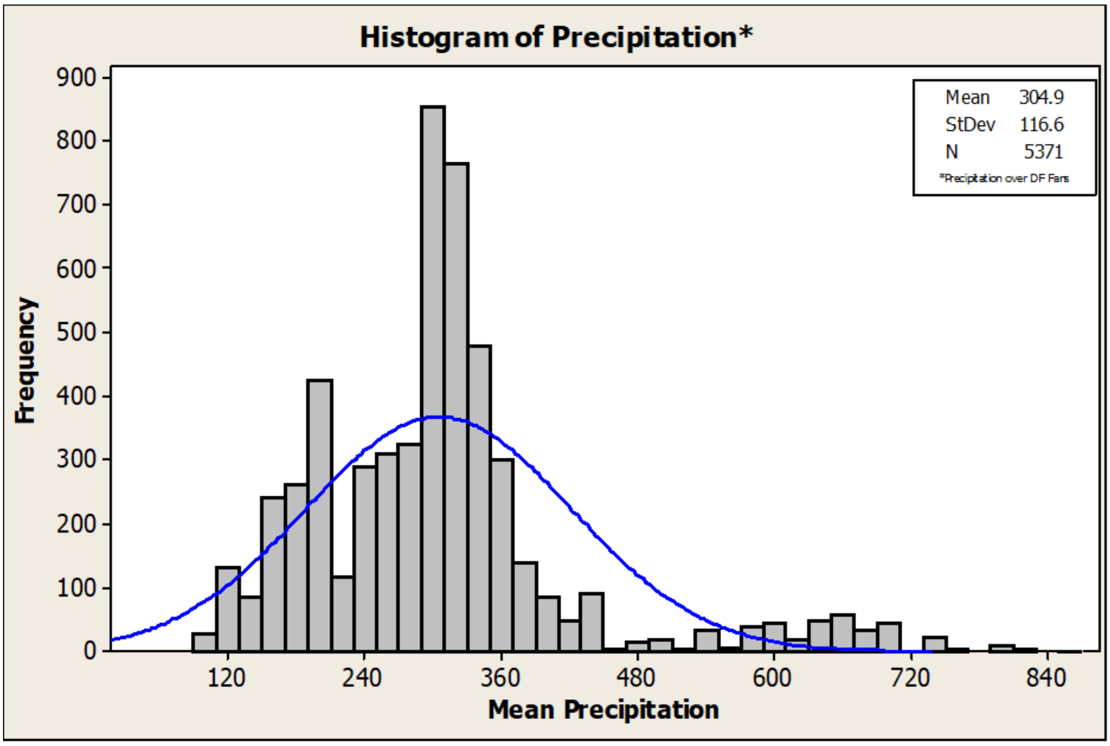

Fig. 6. Mean Annual Precipitation over DF fans with normal curve.

Land cover of debris flow fans

The development of debris flow in the study area has a long history [*Khan et al., 2013; Wasson, 1978*]. The number and scale of debris flow outbreaks in each debris flow gully are different, and the geographic environment in the vicinity of DF fan varies and is influenced due to human activities, making the shapes of DF fans different. The DF fans were evaluated for landcover classes (Table 4). The landcover results (Fig. 4) indicated that larger number of DF fans accounted in barren land and comparable number are on area with vegetation. As the NDVI analysis (Table 2) showed DF fans don't have dense vegetation but sparse green cover, validating our landcover results. Presence of glacier debris class indicates the presence of glacier debris fans in the region, while the presence of DF fans in urban area is concern.

Table 4. Landcover classes evaluated against DF fans.

	Landcover Class						
	Vegetation	**River**	**Glacier Debris**	**Clean Ice**	**Barren land**	**Urban**	**Grand Total**
DF Fans count	2458	27	449	4	2473	124	5535
Percent DF Fans	44.41	0.49	8.11	0.07	44.68	2.24	100

Conclusions

This research documented the surface morphology of DF fans (5535 in number) in Chitral and selected districts of Gilgit-Baltistan using various geomorphological and environmental parameters, majority of which were never envaulted in the region before. Based on DF hazard intensity and return period, all the fans were categorized into three classes viz Medium (37.33%), Low (32.43%) and High (30.24%) having total area of 309.2 km^2. It shows that the debris flow fan in the study area are dominated by the medium intensity fans.

Satellite based image classification proved very vital to assess the surface cover of DFs. Our analysis shows that among different landcover classes barren land and vegetation have highest count of DF fans with 44.41% and 44.68%, respectively. The analysis of geomorphological parameters suggests that the surface of DF fans to be coarse, rocky, having ability to retain a minimal amount of water content, with mean slope angle of 18 degree and present along the valleys/tributaries.

The urban areas located in the high DF hazard zones are limited in number but is a big concern due to threat to human lives. The NDVI values over DF fans can be taken as good sign, as the increased vegetation reduces the sediments movement through these gullies and small streams as they keep soil intact over DF fan surface. This it is concluded that the method implemented is robust and easy for calculating surface characteristics of DF fans in mountainous areas.

Acknowledgements

The authors would like to thank NASA and ESA for providing open-source satellite data, and Google Earth Engine team for providing cloud computing platform. Authors also acknowledge the AKAH Pakistan efforts in developing a comprehensive HVRA database and providing research platform. Authors also would like to acknowledge Mr Deo Raj Gurung for his review and suggestions.

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