



Anthropocene Bearing on Snow-Avalanche Disasters over the West Indian Himalayas: An Appraisal

Siba Prasad Mishra ^{a*} and Arnada Samal ^a

^a *Centurion University of Technology and Management, Jatni, Bhubaneswar, India.*

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJECC/2022/v12i1030772

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://www.sdiarticle5.com/review-history/86672>

Received 14 February 2022

Accepted 27 April 2022

Published 28 April 2022

Review Article

ABSTRACT

The Himalayas is massive mountainous hills of altitude about 2000m to 6500m garlanding India in the north extending about 2500km arc-shaped snowy glaciers covering parts of Afghanistan, Pakistan, India, Nepal, China, and Bhutan at various heights in sub-tropics. Snow avalanches in winter with floods and landslides cause maximum fatalities with increasing vulnerability in West Indian Himalayas (WIH) dropping temperature to $\approx -60^{\circ}\text{C}$. The ignored calamity has encountered unplanned relief to inaccessible areas that warrant a disaster risk reduction (DRR) approach with modern structural interventions under downsizing glacier due to Anthropocene stresses.

The present study envisions the various avalanche occurrences in the three most pretentious states Jammu & Kashmir, Himachal Pradesh, and Uttarakhand, in WIH. Correlation between geological vs meteorological responsibilities such as temperature, earthquake, snowfalls, and Indian summer monsoon with avalanche sorted out and causes depicted. Present investigation is about vulnerability, risk, track, impact, forecasting procedures, early warning system (EWS), disaster risk reduction processes, moderating strategies and other factors.

The inferred results are the cause of avalanche formation, the decline in the glacier area, the increase in frequency, and intensity, and the disaster risk reduction processes including the disaster management action plan (DMAP). The vulnerability area designation, awareness among people, disaster mitigation by public private partnership (PPP) mode, as combined effort on war footing basis by the line departments.

*Corresponding author: E-mail: 2sibamishra@gmail.com;

Keywords: Disaster risk reduction; early warning system; snow avalanche; SASE and BRO; western disturbances; West Indian Himalaya.

1. INTRODUCTION

The avalanche is fast sliding snow-mass movement on the mountain slopes conjoint to icy steep regions when the downslope of steep mountainous terrain drives huge detached snow, ice, and allied debris like rocks and vegetation of mountains. They can be rock initiated, ice instigated or debris triggered. These trivial avalanches/sluffs, which transpire in outsized numbers, are common and unimportant in the Himalayas. The huge avalanches at times encompass large slopes (a kilometer or more in length) with the huge mass of snow, which occur intermittently and are apocalyptic. Humans since evolution exposed to the threat of these sliding Snowmass as homosapiens reside in high altitudes of mountainous regions. The impact of these avalanche disasters has regular exposure to the western Himalayas and the trans-

Himalayan range. Recently, heavy snowfall of up to 2m befell at many places on the high altitudes of the Pir-Panjal range between 16-20 February 2005, 300 people lost their lives resulting in avalanches in Anantnag, Doda, Poonch, Pulwama, Udhampur and Kinnaur (Nepal) districts of J&K. The U'Khand flash flood pointed towards the weakening of rock mass due to freezing. Over. Recently on 22 Feb 2022, seven Indian soldiers were dead in the Kameng sector of Arunachal Pradesh India.

The Himalayas is massive mountainous hills of altitude ($\approx 2\text{km}$ to $\approx 6.5\text{km}$) garlanding India in the north extending about 2500km (Fig. 1). They are arc-shaped snowy glaciers covering parts of Afghanistan, Pakistan, India, Nepal, China, and Bhutan at various heights in sub-tropics. The blocking highways including pedestrian and village roads.

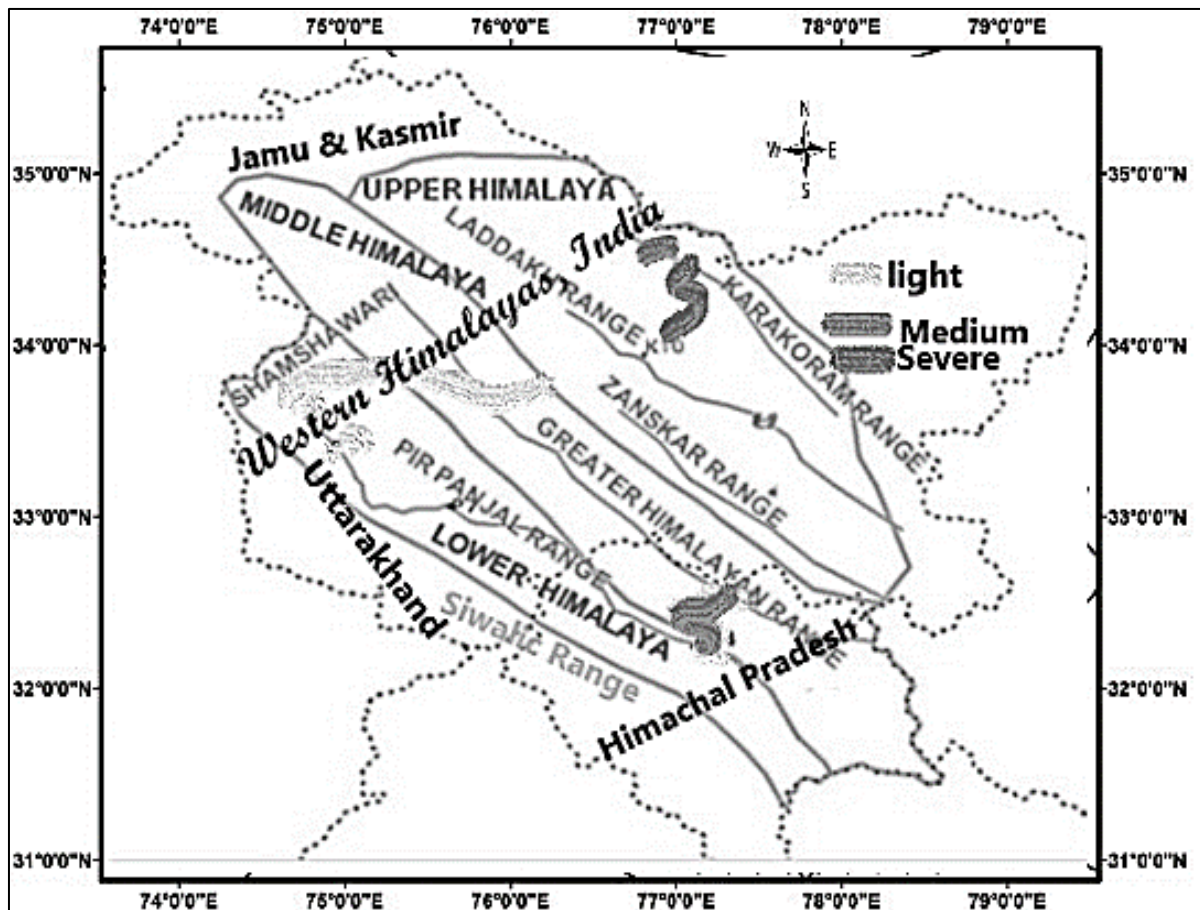


Fig. 1. The Western Himalayas with Avalanche prone areas (Source Modified Gusain et al. [1])

Pir-Panjal Ranges are under disruption of communication due to avalanches on the national and state highways between Jammu to Srinagar (NH-44), Naugam to Kaiyan, Chowkibal to Tangdharand, and many other roads. The climate in the Himalayas altitude based and roads./NH existing are Srinagar to Leh and Bandipur to Gurez, India's border line, road to different passes are frequently visited by Avlanches. Elevation wise western Himalayas are the *Lower Himalayas* (2km to 3,000m), with heavy rainfall and reasonable temperatures, the Greater Himalayas (3 to 4 km) are cooler with snowfall but dry. The Karakoram Range (4 km to 6 km), houses the K2 peak (global 2nd highest) and the Siachen glacier (the border of India, China, & Pakistan). The increased military activities in border areas, the establishment of army camps, and frequent plying of service military vehicles have surged the avalanche activities in Himalayan areas. The Amarnath shrine area needs to be solitary and no chanting of mantras demands to observe a silent zone under a pristine biome.

Indian western Himalayas (WIH) comprises of Siwalic (350 to 1500m), Lower (Inner Himalayas 1500-4500), greater Himalayas and Karakoram range called Tibetan Plateau or Alpine zone (even the third pole in the globe) as per Govt of HP (Disaster Mngt. cell – 2019) (Fig. 1). The area houses the largest numbers of glaciers

beyond the apex poles i.e. North or south poles. Canova's [2] study on avalanche and 150years tree ring transformations in western Himalayan slopes reveals about 500 tree ring anomalies and 38years of avalanche disasters in the area from 1855 to 1970 whereas there are significant upsurges in both numbers of disasters and affected areas beyond the 1970s, (Fig. 2) (Gullet 2018 [3]). Recent avalanches, EQs, and floods arising out of snow melts in glaciers have posed problems to Indian soldiers along the LOCs and border check posts and have taken more than 1000lives since 1986. Many passes are closed during winter for snow/avalanche activities as per Govt of HP, (Table 1).

Few recent avalanche disasters passed through the Indian Himalayas given in Table -1 narrate how frequently such hazards made the life of mountain people in high altitudes miserable. J & K faced avalanche deaths of ~350 in 2005 and 2012 and about 125 fatalities. Siachen, the world's 2nd largest retreating glacier beyond the poles, is 73, 541.7, and 108.3km respectively, downsizing by 5m/yr (Raina et al., 2008 [4]).

From the distribution of available data, the inference is maximum avalanche occurrences during the first quarter months of the year, where the maximum frequency of the disaster is optimum in the month of March (Table 1), Podolsky et al, 2009 [12].



Fig. 2. The avalanche risk areas WIH (Source: Mongabay, 4 May 2018, NDTV 18 Nov 2020)

Table 1. List of recent Avalanche hazards exposed to Indian Himalayas with fatalities and losses

#	Avalanche	State	date	Deaths	Losses	Source
1	Rishiganga/Dhaulti- Ganga hydel Pr.	U'-khand	9-13 th Feb 2022	nil	Scar in snow; flash flood	Kalachand, Sain, WIHG
2	West Kameng;	Arunachal Pr.	6-8 th Feb 2022	7dead	Army guards	WIHG
3	Chamoli	U'Khand	7 th Feb 2021	200dead /missing	27mcum snow (Ronti peak)	https://www.indiatvnews.com/710943
4	Dhauliganga valley	Chamoli, U'Khond	23 April 2021	11 died	Indo Tibet border	Sharma et al, [5]
5	Rishi Ganga valley	Chamoli, U'Khond	7th Feb. 2021	20 dead/ >150 miss.	debris flow induced STDS	Sharma et al, [5]; TOI 12th
6	Solang Village, Gurez	J&K	15 th Feb 2020	18 killed & 200 missing	broke dams/ bridges,	Economic Times15 Feb 2020, 06.04 PM
7	Roshan Post in Tangdhar	Kupwara dist.J & K	18 Nov 2020	01dead/2injured	Security post affected	NDTV 18 th Nov.
8	Tangdhar; Gurez; Kup -wara	J&K;	4 th Dec 2019	03 dead	Near LOC in North Kashmir	Indian Express December 4, 2019
9	Batalik Sector; Ladakh	J & K valley	13 Jul, 2018	09 dead/ 2 rescued	Soldiers at Machhil post	Economic Times
10	Gulmarg ice festival closed	J &K	18 Feb 2017	20 soldiers	Both side border died	Nair A., Ind. Today (Publ ⁿ 20 Feb 2017)
11	Kambhu, Srinagar	J&K, HP	Jan-Apr2014	51dead	LOC, Civilians:	Kumar et al., [6]
12	Derahdun	U'Khand;	3 Feb 2013	2dead	Civilians; WD	
13	Siachen ;Deradun	UKhand;	16 Dec 2012	20 dead	LOC; soldiers	
14	(Lahul &Spiti)	J&K	Mar 2011	2dead	Heavy snowfall	Kumar et al. [6]
15	Gulmarg	J&K	8 th Feb 2010	17dead	Border soldiers	Economic times 8th
16	Pir-Panjal Range WD effect	J&K	16-20 Feb:2005	278(24 soldiers)	4.5m snow fall Gulmarg	Mallik et al. [7]
17	Gulmarg	J&K	Feb:1996		4.5m snowfall	Unit-14 Avalanches: Case
18	Uri Sector; Monang post.	J&K	23 rd -28 th Mar1997	7dead	- 7.0°C Temp. Slab avalanche	Studies; eGyankosh
19	Mahu Mangit, Banihal	J&K	25 th Feb 1998	11dead	3m depth snow pack fractured	
20	Lahaul and Spiti	J&K	March 1991	snow fall Jan-Mar	Transport ceased	Kumar et al., [6]
21	Lahaul &Spiti	Hima.Pr.	Jan 1975	NA	EQ; loss roads	
22	Lahul and Spiti	Hima. Pr.	March, 1978	30 dead	Road/property damaged.	Avlanche atlas [8]
23	Lahul and Spiti	Hima. Pr.	March, 1979	237 dead	Road disrupted.	
24	Pir Panjal ; Rajouri	J& K and Him. Pr.	Dec 1982	≈126 dead	Avalanche and under snow	IMD disaster event [9]

Hima. Pr.: Himachal Pradesh U' Khond: Uttarakhand; EQ: Earth quake; WD- western Disturbance; WIHG: Wadia Inst. of Himal. Geology

Source:www.yourarticlelibrary.com/geography/avalanches-damages-preventive-measures-and-avalanche-prone-areas-in-india/14070; [egyankosh.ac.in/bitstream/123456789/25175/1/Unit-14;Govt of HP \(Disaster management 2019 \[10\] and 2015 \[11\]\)](http://egyankosh.ac.in/bitstream/123456789/25175/1/Unit-14;Govt%20of%20HP%20(Disaster%20management%202019%20[10]%20and%202015%20[11]))

2. REVIEW OF LITERATURE

Avalanches, regular hazards in snowy mountains, victimize people and property accompanying the present climate change (CC), anthropogenic intensity, frequency, and types are changing, distressing more and more of avalanche committal and trauma, Strapazzon et al. [17]. The present warm climate over the Indian Himalayas is welcoming avalanche disasters for the last decade, Ballesteros-Cánovas et al., [2], Giacona et al., [18].

The buried victim's survival is 50% due to asphyxia if extricated for more than half an hour due to ice accretion in the nostrils and mouth cavity or otherwise from accumulated debris-covered over the prey, [19,20,21]. Risk of Hypothermia is common as the repercussion of most natural disasters like floods, earthquakes, Tsunamis even in avalanche risk chain and casualties areas, Wang et al., [22], Zafren et al., [23], Strapazzon et al. [21], Oshiro et al., [24].

Western Himalayas in India is in exposure to frequent landslides and increasing snow avalanches due to earthquakes, warming up, and heightened snow melting prompts light-absorbing impurities (LAIs) like dirt, debris, dust, and elemental carbon (EC). The flow from tributaries contributes to fluvial influx through the rivers the Ganges, Brahmaputra, Indus, and the Yangtze, like snow in mountainous areas of Canada, and Switzerland, Jain N., [25], Sinickas et al., [26], Singh et al., [27], Thind et al., [28]. The risk analysis for future challenges, along with development, geomorphology, and LU/LC (land use and land cover) scheduling is essential because of increased avalanche, and landslide occurrences by using GIS and RS Singh et al. [29]. The West Himalayas have had increasing winter rain, average temperature, and avalanche risks since 1970 with augmented anthropogenic activities, Statham et al., [20]; Puzin et al., [30]. Stimulating landscape features, current orogeny, and meteorological settings are substantial aspects claimed against mass movements initiating avalanche disaster, Alean et al., [31]; Mandal J. [32], Meena et al., [33], Mondal [34].

In avalanches, the gravity slips of mass (rock, ice, soil, debris, and water), ground for remarkable indemnities in high snow-covered mountainous hills globally. The dynamics and the movement of mass under actions of gravity are differing by rolling, falling, sliding, and flowing, Li, et al. [35]. At times, the avalanche is triggered by

eruption, flood, lahar, earthquake, or rockfall or combined, Waitt et al., [36], Podolskiy et al., [12], Sanders et al. [37], Ha et al. [38] and [39]. Density of vegetation, forest, global warming, western disturbances (WD), snow fall and human activity have surged the snow avalanche activities in West Indian Himalayas, Chaudhary et al., [40], Canovas et al. [2], Wester et al. [41], Strapazzon et al. [17], Yang et al. [42], Kanwar et al. [43].

2.1 The Necessity for Study

The avalanche hazard has become increasingly vulnerable to the people, flora, fauna, and ecology of the western Himalayas in India. Apart from natural calamities like temperature rise, the upsurge of carbon dioxide has transformed the past climate. Most strikingly, the surge in anthropogenic activities like vehicular traffic, road construction, agriculture, tourism, military activities, deforestation, and human settlements are increasing the risk and vulnerability of the avalanche in the Indian Himalayas. The climate warming in the Himalayas and continuous melting of snow and ice in the peaks and glaciers may bring alarming modification in the scale, extent, and annual rate of incidence of avalanches that shall shift ITCZ, and alter the mountain landscapes and associated socioeconomic systems of the area. The decadal dry periods prevailed in India ranged from 1961 to 70, 1971 to 80, and 1981 to 90, [44].

It is high time to have a scientific investigation of the snow-avalanche Hazard and to impart well-coordinated action with improved risk management. The players, who monitor the threats and impacts, are explored from various source publications. The favoring organizations are India Meteorological Department (IMD), Snow & Avalanche Study Establishment (SASE), and available literature on print and TV Media discussed.

3. METHODOLOGY

There is a huge knowledge gap about statistics of an avalanche as a disaster in West Indian Himalayas (WIH). The death, casualties and other losses are less in ancient literatures in comparison to floods, droughts, and other natural disasters. Media is reporting regularly deaths, missing reports and losses due the avalanches after 1960 onwards in Siachin and other passes in settlements, military camps and road blockage at high altitudes of western Himalayas during

winter due to snow avalanche. Present review is an attempt to know the mortalities, trauma, settlement and other environmental losses associated with the avalanche disaster from site visit, print and electronic media.

Correlation between geological vs meteorological such as temperature, earthquake, snowfalls, and Indian summer monsoon with avalanche sorted out and causes depicted. Present investigation is about vulnerability, risk, track, impact, forecasting procedures, early warning system (EWS), disaster risk reduction processes, moderating strategies and other factors.

3.1 Snow Climate in WIH

The avalanche areas classified as maritime (Huge snowfall with moderate temperature) or snow climate (less temperature and mild snowfall). WIH falls under maritime category. The altitude, slope, aspect, and ground conditions induce avalanche in WIH are >3200m, 30° to 45°, SE to SW, forest, boulders, Tall grass and bushes [45,46].

3.2 Earthquake and Avalanche Coincidences

Seismic events cause avalanche events and vice versa [13]) (Fig. 3). The notable earthquakes that

transpired in WIH are Kangra (1905/ M- 8.0), Kinnaur (1975/ M- 6.7), Dharmasala (1978/ M- 5.0), and (1986/M-5.7) in Himachal Pradesh, as per National center for disaster, ND. The receding rate of the WIH glacier at Barashingri, HP was 44.3m/year was the highest and the minimum was 13.3m/years, Podolskiy et al. [12], NDM book HP, Ch- 14 [14].

3.3 Major Snow Avalanche on Earth

Past avalanche deaths were about 10000 in Italy 1916, 4000in Peru in 1962, 2200 in Peru in 1970, 200deaths in Lahaul Valley avalanche, India during 1979, and 42deaths in Gokyo avalanche in Nepal during, 1995 (Wiki data). Afghanistan, Pakistan, India, and Nepal are the worst sufferers of snow avalanche impact. Avalanche calamities have taken 216 lives on 1st Mar 2015 (NDMA data), 124people on 27th Feb 2015, in Panjsir province, and Salang pass in NE Afghanistan. Nepal is not free from avalanches and EQ. on 11 May 2015; the Hindustan times of Nepal reported of 200people trapped in Langtang valley (Rasua) in the Kyanjin Gompa area. The data reveals that the focusing area of avalanche in the world is Afghanistan, India, Peru, Japan, and Italy, etc. McIntosh. The Himalayan arc in India's north has become prone to avalanche, Gahalaut [16].

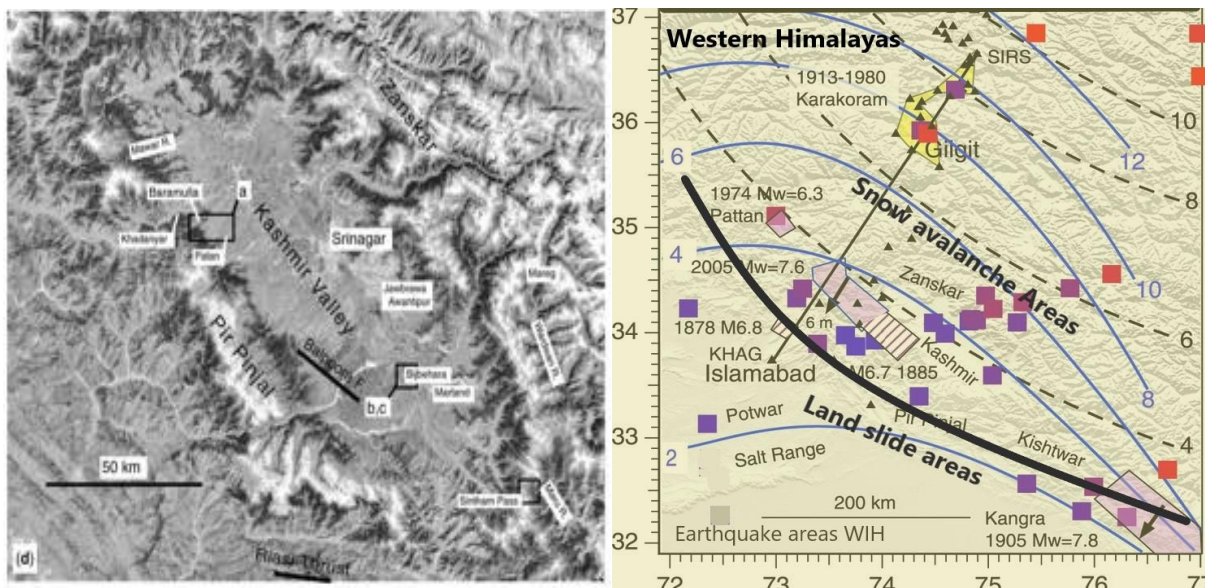


Fig. 3. EQ/avalanche areas in Lower, upper and greater Himalayas, (Pirpanjal, greater Himalayas, Zaskar, Laddaku Korakaram range) Source modified: Bilham R. [15]

3.4 Geology of Western Himalayas

Indian Himalaya has, extends for ≈2500 km as a chain of folded types of mountains garlanding from east to west (72°96'E long. and 26°N to 37°N lat.). These furrow-type chains of mountains are datable to the upheaval of the Himalayas from the Pleistocene epoch consequent upon the thrusting of the Eurasian Plate. The Himalaya's perform as an obstruction to the glacial katabatic airstreams flowing from Central Asia but depriving India that maintain the subcontinent warmer. The high altitude mountains has unique diversified biological, frosty, and fluffy biome. The frequency, amplitude, and intensity of the snow avalanche are higher in the western than in the northern Himalayas (Laxton et al., [47]).

The complex geology and the diverse disparities of geological settings in snowy over-burdens make it difficult to forecast an avalanche for the meteorologists, scientists, and forecasters working on such disasters in the area [29].

The avalanche occurs under conditions of snowstorm Strong western disturbance when the overburden surpasses 200kg² after filling the terrain irregularities like Rishiganga and Dhauliganga powerhouse project in the year 2021, (Fig. 4(a) & Fig. 4(b) (Singh et al, 1998; Podolsky [12]).

3.5 The Anastomosis of Drains

The Indian Himalayas has a huge number of anastomosed channels conjoined to give large

rivers like the Indus, the Ganges, and the Brahmaputra. The Indus is flowing in the western segment whereas the other two have formed the largest delta in the world, the Ganga-Brahmaputra delta in the east. However, the Indus River has a large number of gullies, drainage channels, Branch Rivers debouching the Arabian Sea flowing through three states, the Himachal Pradesh, Jammu, and Kashmir, and Punjab (Fig. 5(a) and Fig. 5(b)).

3.6 Role of Meteorological Players

Western disturbances (WD's) and the exorbitant mountainous ranges (seven) play a pivotal role in deciding the geological factors in the Indian Himalayan range. The impact of the meteorological disturbances is Surface Atmospheric Temperature (SAT), Rainfall, Snowfall, and associated hazards like cold snow hazards, high floods, and extensive Avalanche geophysical incidences. The IMD started to study the glaciers in 1972 through a geological survey of India, and the Dept. of Science and Technology under the Hydro met directorate, to have study about water balance, climate, seasonal snow spread, and snowmelt in the Himalayas [44]. Studies reveal an increase in CO₂ conc, SAT in Indian Himalayas, global warming, lowering of WD influence in the area, shifting of ITCZ (Inter-tropical convergence zone i.e. (average of out-going long-range radiation OLR) have caused significant transformations in the geo-hydro-bio atmosphere of the mountainous expanse. (Dimiri et al., [49], Naresh Ku et al., [50], Mishra et al. [51], Dimiri et al., [52].



Fig. 4 (a). Dhauliganga hydropower project-affected breaking of the glacier at Joshimath Feb. 7, 2021, Mint. **Fig 4(b):** The Avalanche risqué area in Himachal Pradesh Feb'2019

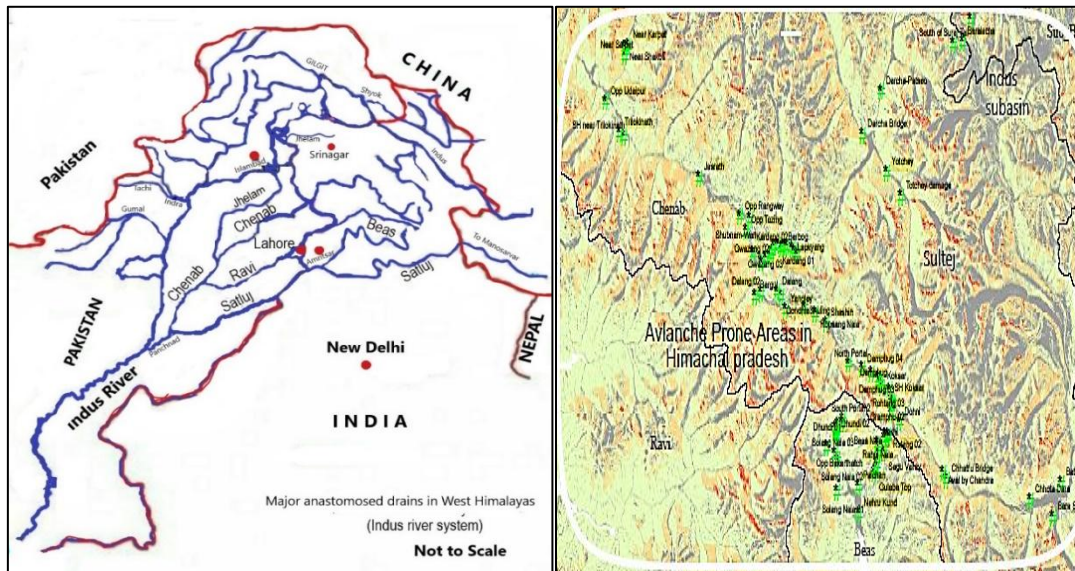


Fig. 5(a): The WIH anastomosed river system. Fig. 5(b): The major avalanche areas in Himalayas (Source: Raina et al. [4], Taru [10])

3.7 Activities of Forecasting Agencies

The worst sufferers of snow avalanches are the son of the soil, soldiers safeguarding the motherland, the service providers like pavement, Dam, transport other outside people in the expanse. It is pertinent to provide the stakeholders with expert advice from local line departments, the Mountain Meteorology Division (MMD) of the National Weather Forecasting Centre (NWFC) under IMD, and particularly SASE under the aegis of DRDO. The AFC (Avalanche Forecasting Centre) and MMC (Mountain Met Centre) units have developed stochastic and soft computing models to predict avalanches for immediate dissemination in the hit areas.

SASE developed avalanche prediction practices using soft computing models, through the GIS technique, Remote sensing data utilization, and UAV survey for avalanches in the Himalayas. They have surveyed, designed novice techniques, and built avalanche control structures in the area. Through mitigation schemes, SASE has developed various types of control structures in strategically focused areas. SASE has recommended solutions protecting the highways, railway lines, ropeway, chutes (Dhundi), and the protection of transmission lines, (Nayak R., 2005, updated [53]).

4. CAUSE OF AVALANCHES

There two types of avalanches are either loose snow avalanches or slab avalanches with further,

sub-classified depending upon snow involvement (dry, damp, or wet), cover, origination in a surface layer or total snow cover and fall during the avalanche hazard. Avalanches prerequisites steep slope, depth of snow cover with an intermittent weak layer, and a trigger to initiate drive like earthquake (Singh et al, [54]). The fall of snow mass is due to the slightest misbalance of snow mass causing unstable equilibrium on a steep slope when the natural angle of repose is exceeded. Later-generation of high momentum accelerates with more snow mass and slides the snow and debris mass onto the ground. Avalanches of dangerous size, originate on steep slopes with angles of repose ranging from 30 to 45°. Avalanches originate in slopes ranging from 45° to 50° sluffs; common are small avalanches in some cases. The mud or snow avalanches can have to trigger externally by Icefall, earthquake tremors, rock falls, thermal changes, blizzards, and anthropogenic loud sounds such as shouts, machine noise, and sonic booms (Singh et al, [55], Mishra et al., [56]). The change in ecology, anthropogenic military activities, and Global warming have triggered avalanches in the WIH.

5. TYPES OF AVALANCHE

Generally, the dry, loose snow avalanches are small and few achieve sufficient size to cause damage. With the onset of melting, the wet loose snow avalanches are common. They grow more occasionally, and reach a destructive size, especially when confined to a gully. Slab

avalanches initiate in the snow with ample internal cohesion to enable a snow layer, or layers, to react mechanically as a single entity. They accumulate to generate wind that drifted very high in the hard slab. A dangerous, unpredictable, slab avalanche (wet, dry, new, or old), that fractures freely along a characteristic line, sliding initiated when the slab face stands perpendicular to the slope either partly or wholly along a mountain slope along the fracture as stress release zone, that is variable. The gross sub-division is full-length or surficial dry and wet avalanches (Hao et al., [57], Bodaballa et al., [58]). The most damaging slab avalanches comprised of dry snow typically spawn as a dust cloud like CB (cumulonimbus) cloud. The whirling snow slide created from soft slabs was identified as powder snow avalanches. Snow crystals mixed with air to form an aerosol, which appears as sharp confined dense gas falling down the gradient with the snow-head. The high dense snow has enormous destructive power though at lower velocity.

6. THE TRACK OF THE AVALANCHE

Heavy snowfall for a short extent has a greater chance of avalanche manifestation. Avalanches reach speeds of up to 200 km/hour and can exert great forces leaving a track, smashing structures, and can uproot or snapping off large trees. Tree rings depict the number of avalanches in the area exposed. Occasionally, an avalanche can run way up the slope across the valley from the avalanche path repeated exposure. Such paths have a panoramic view and the lands are less prone to pass many winters, even decades without a serious avalanche (Such an period is 1940-1950). Avalanches are independent of specific terrain features. They prefer to follow narrow gullies or ravines to travel. They seldom travel in broad, less varying slopes, even in ridges or spurs. The longitudinal profiles of the paths may be concave, convex, or stepped. The Convex slopes are more vulnerable to avalanche hazards than concave slopes. On stepped paths, small avalanches will often stop on a bench some distance down the track while larger ones will run the full length of the path.

6.1 Avalanche Hazard Mitigation Zoning

In the Indian Himalayas, large numbers of avalanches have been reported having avalanche sites extending more than one km and snow volume of thousands Cum. An avalanche hierarchy consists of Formation Zone, Middle Zone, and Runout Zone. Avalanche Hazard Mitigation using Control Structures and Artificial Triggering of Avalanches. Various control structures are categorized based on the avalanche zone. These control structures are designed to keep in view the specific nature of particular avalanche sites (Table 2).

The other way of zoning is Zoning Avalanche areas are red zone, Blue zone, or yellow zone. The utmost perilous zone is that where avalanches are recurrent. Such avalanches have bearing pressure $> 3 \text{ MT/ m}^2$. The Blue Zone has avalanche pressure $< 3 \text{ MT/ m}^2$ and housing and livelihood activities are permitted with proper preventive measures but must be vacated at the advent of a storm on warning. In the yellow avalanches zone, the hazard seldom occurs.

7. THE IMPACT OF SNOW AVALANCHES

The avalanches damaged people, flora or fauna, and even manmade structures if obstruct the way. Over 1,000 Indian soldiers, including over 35 officers, have lost their lives in the Siachen Glacier-Saltoro Ridge region since April 1984. The debris that emerged blocks highways, rail, and roads of any kind. The huge thrust and fast velocity of moving snow, debris, and the burial of the areas in the run-out zone. During summer, the avalanche-prone areas are less vulnerable and at least risk but deserted in winter. The land use (LU) in an avalanche prone area must not comprise structures intended for wintertime and early spring occupancy. Structures as well as power lines, national transportation roads, railroads, and other LU, within the avalanche routes and run-out areas. They are to be appropriately designed against the lateral swaying impact including all deterrent measures prescribed by IS code and NDMA guidelines 2009.

Table 2. The Avalanche prone areas zoning and the hazard mitigation measures/structures

#	Avalanche Zone	Hazard Mitigation Measures/ structures
1.	Formation Zone	Snow Bridges, Snow Rakes, Snow Nets, Snow Fence, Jet Roof, Baffle Wall
2	Middle Zone	Deflecting Structures, Snow Galleiy
3.	Runout Zone	Retarding or Diverting Strnictures, Catch Dams

8. THE AFTERMATH OF THE DISASTER

Since after the myth of the disaster, everything is under the debris and snow, mostly in remote places, search and rescue operations are mandatory to address the emergency. The seven 'D' impacts mainly are death, disability, disease, distress, damage to Health Services, damage to the Economy, and Damage to the Environment. The fatalities related are 55-65% (mainly due to suffocation), but the rest who survived are in urgent need of medical attendance otherwise they die from Hypothermia or trauma injuries. The self or companion risqué become crucial and locating the victims has become easier by use of GIS, DGPS, and UAV fixed with sensors and cameras. The equipment used is Emergency Position Indicating Radio Beacons (EPIRB) fixed with a global positioning system. SASE at present not involved in risqué operation, it is high time to create public or community awareness and techniques of rescuing with avalanche forecasting network on PPP mode. The only option is the involvement of the community with expert personnel in public-private partnership mode to address the problem of search and rescue services to be in discipline (Das et al., [59], Muhammad et al, [60], Shugar et al., [61], Dematteis et al., [62]).

7.1 Impact on Flora and Fauna

Global warming contributes to an upsurge in the frequency of annual avalanches in the Western Indian Himalayas (WIH). The dendrogeomorphology study of tree ring data (150YBP) and linked it with snowfall data by Ballesteros-Concova's team [2], in 2018 to track the geospatial avalanche effect on the tree trunks. The WIH houses about 57 million people and acknowledged as one among the 34 "biological hotspots" of the globe, which is changing with the change in climate Tiwari et al. [63]. The inference was the sparse occurrence of avalanches pre-Anthropocene and even none from 1940 to 1950. Then gradually increased from 1970 onwards and in the 21st century, the hazard frequency is high and regular Bob Yirka [64].

7.2 EWS for Snow Avalanche Hazards

Early Warning Systems EWS employ two methods to predict avalanches, like snow cover structures (fault patterns), particularly for slab avalanches. The other method uses climatologic meteorological factors like temperature, wester disturbance, type, pattern, and quantum of

snowfall, snowstorms, etc. The snowmelt is the common and prime cause of the disaster; the major inputs to forecasting models are snow cover, terrain, and atmospheric meteorological parameters. GIS technology using Satellite RS data is considered the most efficient tool against the prediction models. The satellite data used are MODIS, AWiFS, AVHRR, LISS-III, WiFS, PAN, Cartographic Satellite (CARTOSAT), I KONOS, Quick bird, etc. During cloud cover, the microwave (AMSR-E, SSM/I, Radar sat, ENVISAT) imagery is in use. The Quick Response Teams (QRTs) are equipped with gadgets /equipment as State Disaster Management Authorities (SDMAs) in alliance with District Disaster Management Authorities (DDMAs), and NDRF.

7.3 Hazard Protection

The increased military activities, communication routes, escalation in winter tourism, built of hydroelectric projects (HEP), transmission lines, and upsurge of urbanization in snowy areas. Protection against avalanches warrants riskless and safe buildings, roads, townships, and growing projects in these areas innocuous from avalanches. Judicious action plans, safe zoning procedures, and strict construction adherence by experts are the wise solutions. Failing the risk avoidance, in the case of transmission/power lines, roads, and railroads, the stipulations to reduce with the implementation of appropriate structural controls and safety measures. From the old field data and historical evidence, avalanche-prone areas have restrictions on building of structures involving winter local use. Agriculture, mountaineering and recreation activities only allowed in the non-avalanche months. Explosive techniques either were in practice for the cautious relief of snow mass from avalanches by many smaller, or controlled avalanche releases. It is wise to avoid large disparaging avalanches.

Engineering structures for the control of snow avalanches are:

- i) Supporting structures in the formation zone prevents initiating or retarding movement before the snowball gains momentum.
- ii) Retarding earth mounds or stone/concrete walls and terraces, rigid structures built in terraces or cliffs Fig. 6(f).
- iii) Runout zone deflecting and retarding structures push the dropped snow mass away from structures in dire locations.

Massive structures of earth, concrete, or rock as breakers, rough tri/ or tetrapod's, and setting of crosscurrents erections facing the snow current can ameliorate the impact of the huge snow mass of the avalanche.

- iv) Direct protection to individual structures avalanche sheds built immediately adjacent to the target.
- v) Avalanche shelters roofs over transport routes or rail lines that allow to pass avalanches overhead, Fig. 6(d).

The border roads organization (BRO) along with SASE, undertake the construction and maintenance the network of roads in the high snow-bound mountains in WIH. They include roads connecting Leh (J&K), Sikkim, Arunachal Pradesh, Himachal Pradesh, and Uttarakhand. They have the duty for clearance operation of snow-avalanche. The monitoring, identification, segregating zones, and recording of new areas of avalanche is the responsibility of the BRO and the SASE. The forecasting of snow avalanches, and the construction of avalanche combating structures, detection devices, protection kits, and

marking of the winter route is the duties of SASE and BRO.

8. ARTIFICIAL TRIGGERING BY EXPLOSIVES

Artificial triggering (AT) used in avalanches to drop the calamitous impact. It is dynamic and economical technique for moderation of avalanche hazards. The artificial triggering method regulate the activity time and size of the avalanche. AT method uses generation of blast waves generated by the explosion to apply additional pressure loading at high strain rates to the snow layers and split them into fragments. It causes the release of unstable snow-mass in the form of a small snow avalanche. Successful artificial triggering involves continuous evaluation of snowpack conditions to identify the suitable window for the application of explosive loading. The target areas where triggering actions are needed are Cornice prone areas for artificial triggering. The making of Artificial Avalanche by Triggering using 84mm RL by Gulmarg Indian Army in collaboration with SASE.



Fig. 6 (a). Snow bridges



Fig. 6(b). Guywires, snow cable nets



Fig. 6(c). Snow fences in avalanche area



Fig. 6(d). Jet roofs avalanche prone area



Fig. 6(e). Snow avalanche dams



Fig. 6(f). Deflecting berms

8.1 Avalanche Moderation Processes

Retarding mounds near Shri Badrinath Shrine and the large monolithic stone (Kedarnath) in the runout zone of an avalanche had saved the temple in the recent past. The common practices of avoidance avalanche impact are land use (LU) precincts, transitory evacuation, or artificial triggering. The constant rise in people and their activity in the area has warranted either moderation or prevention of initiation by building structures like damming, retarding mounds, snow bridges, gully wires, snow fences, etc.

However, the common hard structures to moderate, prevent initiation and protect structures are (a) direct protection targets, Pavements, rail lines;(b) deflecting and/or channelizing rolling snow;(c) blocking and storing snow by dams; (d) backing up snow initially, and (e) reducing avalanche hazard frequencies baffles or fences (Fig. 6(a) to Fig. 6(f)).

9. AVALANCHE HAZARD MITIGATION WIH

SASE with Cryosphere Science and Technology deploy and facilitate troops for operational mobility and precision avalanche forecasting in *western Indian Himalayas (WIH) avalanche-prone areas covering J&K, HP, and Uttarakhand*. Their Mountain Meteorological Centre is at Srinagar (J&K), Sasoma (J&K), Jammu (J&K), and Joshimath (U. Khand), through HQ SASE Manali (HP) covering a 2000Km² area. SASE established observatories and (AWS) automatic weather stations at altitudes up to 5500 m (M.S.L) in Siachen Glacier. SASE has mapped using GIS/RS techniques, the avalanche sites, and routes/road axes in avalanche-prone areas for both Army and civilian movement areas. Avalanche awareness programs were conducted

with the display of personal protective equipment (PPE) for the people from the army along with the civilian in avalanche-susceptible areas in WIH, particularly in the Central and Western Himalayas. They focus on:

- i. Avalanche forecasting in mountain weather
- ii. Mitigating avalanche hazard by artificial triggering and constructing control structures
- iii. RS/GIS technology for extracting terrain and gathering snow cover information
- iv. Developing models, and simulations of snow cover and physic of avalanche
- v. Observatory setup network and instrumentation in high altitudes

Avalanche forecasting is practiced at various spatial scale levels. The common models used are k-NN Models (k-Nearest Neighbors or eNNio model).

10. SOFT COMPUTING METHODS

Since the optimization of the avalanche hazard problem is complex, cannot use any ongoing analytical optimization procedure. Some modern techniques like NIO (Nature-Inspired Optimization) techniques considered providing better results than conventional Algorithms, like PSO, (Particle Swarm Optimization) or ABC (Artificial Bee Colony). The other wavelet based forecasting (WRF) model considered better weather forecasting tool used for 6-days forecast, by use of the eNNio model. Other parallel programming NIO techniques used is ABC model, that uses the compute-intensive. Hidden Markov Model (HMM) used for avalanche forecasting in Pir-Panjal and Great Himalaya and a Decision Support System (DSS) for Karakoram Himalaya using Multi-Criteria Decision Making (MCDM) problems. SASE has responsibilities to

identify avalanche zones, safe launch location, the time of artificial triggering, and safety during artificial triggering practices at Gulmarg site, J&K in Feb. of 2018.

11. NUMERICAL WEATHER PREDICTION

During winter, austere weather events like heavy snowfall with strong gale wind occur in the Western Indian Himalayan (WIH) region due to the drive of synoptic systems called (WD's) that cause snow avalanches. Precise forecasting of WD's, wind, temperature and precipitation plays vital role for cause disaster, the snow avalanches in the Western and Central Himalayas. Due to very high altitude, inaccessible areas the observation data availability is meagre in those no man's land except the satellite data. Based on simulation of those predicted data, forecast for the area by using WRF model (ARW-WRF; model version) provided to the people of J&K, HP (Himachal Pradesh), and Uttarakhand (U' Khond) states in WIH.

11.1 Slope, Aspect, Relief, and Rugosity

It is found that the avalanche generally occurs in mountainous having slopes ranging between 20° to 60° but the frequencies are very high when the gradient is ranging from 30° to 45°, which is the best angle of repose. The leeward wind and solar exposure initiate avalanche profiles on snowy slopes.

The surface slope facing the sun decides to have a profound impact on the snowpack and hence the wet avalanche in mid-amplitudes. The incident insolation is more direct on the southern slope than the northern slope. The northward and east-facing slopes are exposed to less heat so colder in NH (Northern Hemisphere). In WIH, most of the mountainous slopes faced towards India are either North or NE, or East. The WIH is highly prone to avalanches with less relief.

The roughness of the rolling slope of the terrain behaves as either free sliding or a cohesive layer that can trap snow during descending the slope. Bald surface, grass covering, and mountainous flora having less cover perform as a perfect sliding slope. Big trees, bushes, orchards, and shrubs, help to resist the role of snow along the downslope Panditra et al., [65]. Intervening terrace of water bodies or smooth herbs makes the surface idle rolling surface that can moderate snow avalanche hazard Risk Assessment, Himachal Pradesh, [10].

The avalanche risk index is a multiplicative function used for calculating.

$$\text{Risk index} = f(S, A, L) \text{ Where: Risk index} = \text{Avalanche risk index; } S = \text{Slope; } A = \text{Aspect; } L = \text{Land cover} \quad (i)$$

The HP state disaster risk assessment, 2015 and reported that the slopes <20°, 20-30°, 30 – 45°, 45 -60° and >60° are 8220km², 9308km², 13801km², 4139km², and 253km² respectively. As per the Hazard, Vulnerability & Risk Analysis atlas of Himachal Pr., [10], the optimum range of angle for the high vulnerability of avalanche is 30° - 45° the slope angle.

12. GIS / RS USE FOR AVALANCHE STUDY

GIS/RS are the best use to analyze the avalanche for its occurrence, prediction, or devastation, AE (Analog Ensemble) prediction system based on real time QPF's for microscale weather forecast developed by the SASE. Six meteorological observatories at various ranges Shameswari, Pir-pinjal, great Himalayas and Karakoram have been working in NWIH. These AE systems, an independent local organization, which utilizes ground, based meteorological observatories to observe daily meteorological parameters, and meteorologists generate local microscale weather forecasts for coming 3-days in advance and test the previous day forecast already transmitted over NWH. They generate forecast for meteorological parameters like surface air temperatures (maximum, minimum, and ambient in (UTC) universal time coordinated scale), surface atmospheric pressure in millibar, wind speed/direction in knots, relative humidity, and of upper air pressure with wind velocity. (Khatiwada, et al., [66], Yriyan et al. [67], Altaweel [68]).

13. DISCUSSION

The avalanche (snow) is common in winter extreme climate, snow fed areas, high relief with large slope (>1 in 300) and triggered by earthquake. The avalanche disaster is sporadic in eastern and infrequent in central and regular in western Himalayas in India. The height favourable are >3km. IMD has reported very little past historical evidence before the epoch Anthropocene (1950) being the warden of disaster. The avalanches statistics reveal the disaster are in upsurge trend from 1970 and onwards. The anthropogenic activities in the

glaciers, military accomplishment, increased earthquake tremor, global warming, erratic onset and withdrawal of monsoon, unrest BoB and the Arabian Sea can have influenced the rise of snow avalanches in the western Himalayas. In

recent past (08th Feb 2022) an avalanche in Arunachal has taken seven Army personnel which is uncommon in Northeast Himalayas (The print; 12 February 2022).

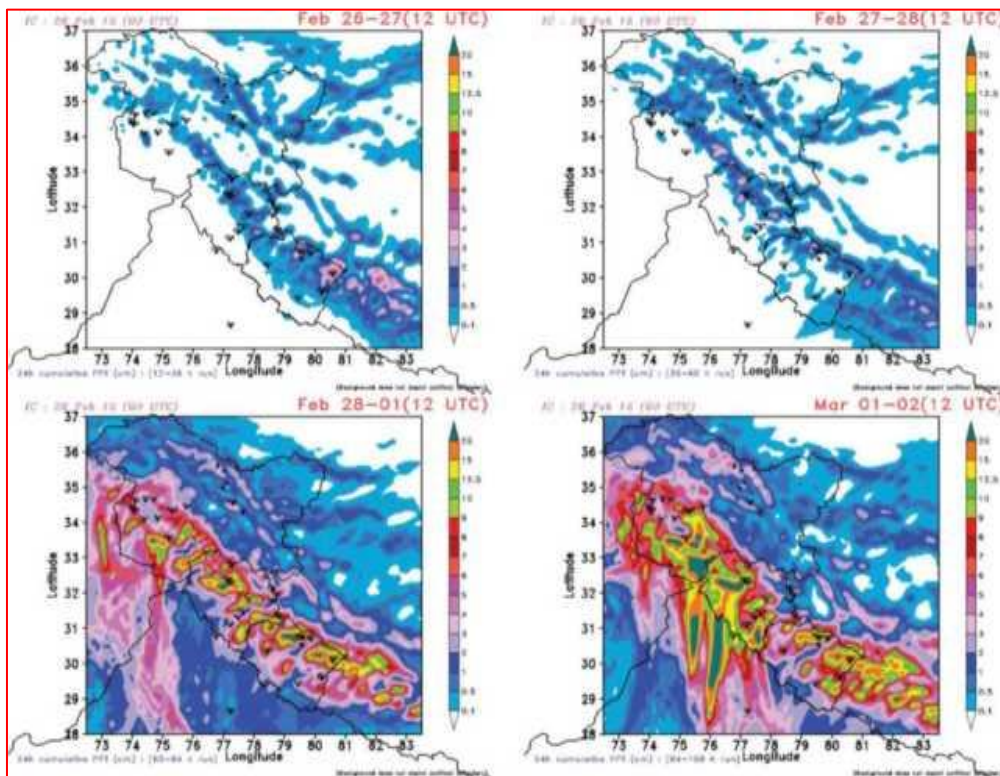
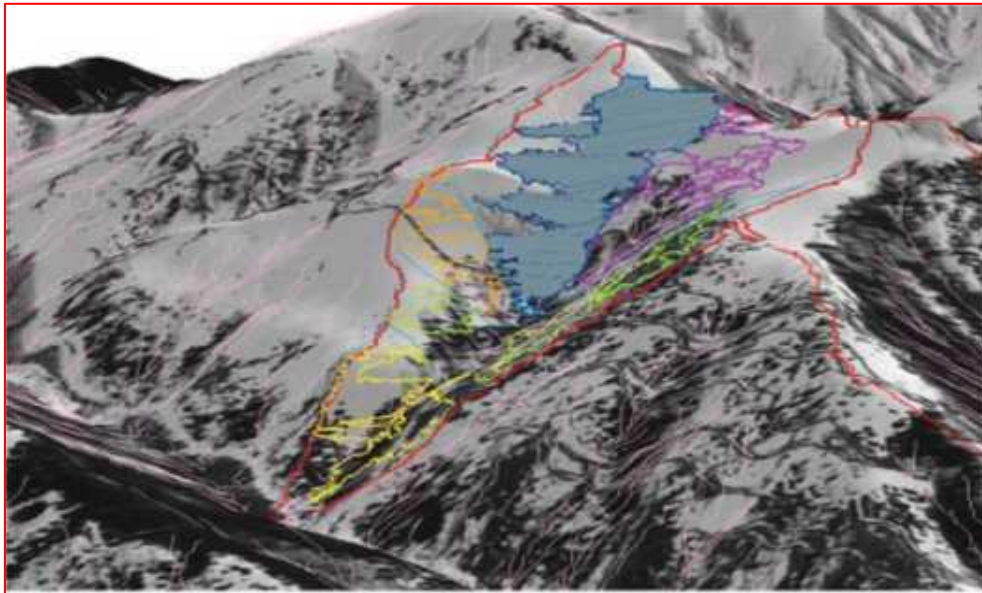


Fig. 7(a): The slope & hazard polygons by GIS-based spatial model; Fig. 7(b): Precipitation forecast over west/central Himalaya by WRF mesoscale in 9X9 km resolution model (Source: Google)

The States of J&K and Himachal Pradesh have highly vulnerable followed by Uttarakhand. Snow- avalanches remotely affect northeastern states like Sikkim and Arunachal Pradesh. J&K state has high interstate connectivity in hill slopes. Most of these roads have the risk of landslides at lower altitudes and upper reaches by snow avalanches. The village roads wind up on way to some of the important passes on Pir-Panjal and the Great Himalayan range during snowfall. The BRO or the state roads organization maintains the interconnectivity within various valleys. The mitigation and avalanche challenges are shared by the state, BRO, central, SASE, and the defense organizations. The responsibility for road clearance, evacuations, pre, and post-trauma attendances, issuing of avalanche warnings, and maintenance of highways, railways, and airports along with all short-term measures shared by all. Poor coordination at times throws the affected victims in distress, as so many people's responsibility is no man's accountability. Initially, people have chosen hit and trial methods to safeguard themselves depending on the relief system for facing hazards but the DRR approach is deployed with adequate EWS. In past, people were consulting agencies like the SASE or

State Government rescue units to address at the time of hazard occurrences. Now print, cloud data, and electronic media are updated to the aware public of the recent developments. Factors affecting snow avalanches (dry or wet) in the WIH area are a strong western disturbance, heavy snowfall, snowstorms, earthquake tremors, industrialization, heavy transportation activities, vibrations, and flash floods, etc.

14. RECOMMENDATION FOR AVALANCHE DISASTERS

On move to avalanche prone hazard and the areas the action plans warranted are (Fig. 8).

Over exploitation of Himalayan ecology, geology, mineralogy, hydrology, Indian summer monsoon and human resources have put the WIH to severe climate change prospective inviting weather that is more disastrous. Steps to protect such road axes from avalanche threats by putting control structures in the path of avalanches are in progress. Such control structures are existent on the National Highway-1 A (J&K) and at Badrinath (Uttaranchal). Since controlling avalanches action plan permanently, EWS warrants

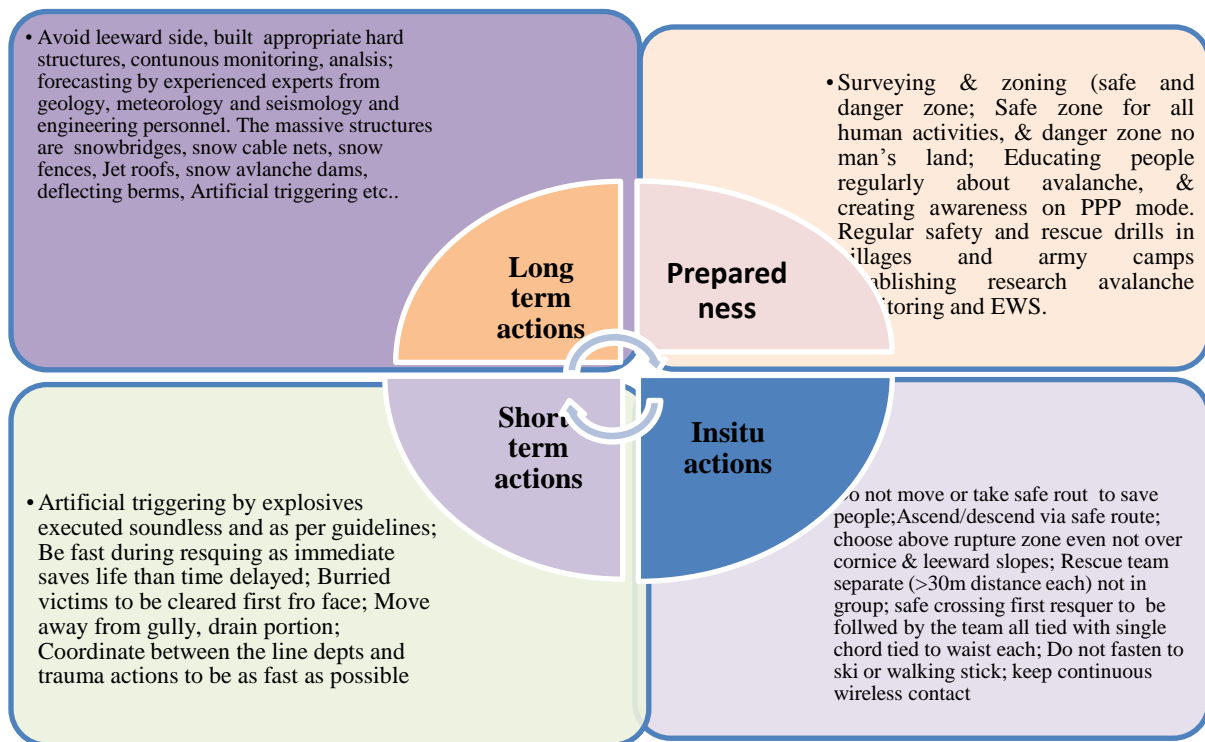


Fig. 8. Action plan framed for the avalanche prone areas in WIH

improving avalanche-forecasting techniques. The practice of DRR by SASE needs war footing approaches. Regular researches, workshops, training programs, etc. need to have widespread awareness, impact assessment, and short and long-term mitigation activities avalanche hazards.

15. CONCLUSION

Avalanches in the Indian Himalayas are a recurring phenomenon. During Anthropocene, the epoch avalanche threat has surged up in high altitudes and steep slopes of snowy WIH steep gully. Previous combating avalanche confined to only relief. Present way of slamming a disaster base upon disaster risk reduction adaptations. They are:

It is of opinion that most of the snow avalanche exposed areas are >3500m altitude, slopes within the range 30-45°, north-facing convex slopes.

The combating avalanche in sloped hilly mountainous areas with no or little, mostly among uneducated mass is a hard nut to crack.

The avalanche exposure is preparedness, training, proper zoning, preparedness, DRR risk assessment, accurate forecasting, and permanent preventing structures, and all combating measures to follow strictly.

The strong coordination between the line departments of the government and DRR responses on PPP mode during, pre and post disaster period shall reduce the risk, vulnerability, impact of the increasing frequency of the avalanche disaster.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Gusain HS, Chand D, Thakur NK, Singh A, Ganju A. Snow avalanche climatology of Indian western Himalayas. Proceedings of symposium on snow and avalanche, 6-10 April, SASE, Manali; 2009.
2. Concova's BJA, Trappmann D, Madrigal-GJ, Eckert N, Stoffel M. Climate warming enhances snow avalanche risk in the Western Himalayas. Proc Natl Acad Sci USA. 2018;115(13):3410-3415. DOI: 10.1073/pnas.1716913115
3. Gullet S. Warming increases risk of snow avalanches in the western Himalayas. University De Geneva; 2018. Available:<https://dendrolab.ch/warming-increases-risk-of-snow-avalanches-in-the-western-himalayas/>
4. Raina VK, Srivastava D. Glacier atlas of India. Geological Society of India, Bangalore, India. 2008;1-316.
5. Sharma S, Sati SP, Sundriyal YP, et al. The 23rd April '21 Snow Avalanche, Girthi Ganga post the 7th February '21 Rishi Ganga Flash Flood: Are these Events Linked to Climate Warming in the Western Himalaya? J Geol Soc India. 2021;97: 975–979. Available:<https://doi.org/10.1007/s12594-021-1811-2>
6. Kumar J, Sriram. Factors affecting snow avalanche. IJSRD – Int. J. for Sci. Research & Dev. 2014;2(10):1-4.
7. Malik IH. Spatial dimension of impact, relief, and rescue of the 2014 flood in Kashmir Valley. Nat Hazards. 2022;110: 1911–29. DOI.org/10.1007/s11069-021-05018-8
8. Avalanche Atlas. Manali-Leh Road. Pub. Snow & Avalanche study, Manali, Himachal Pradesh, India; 1991.
9. India Meteorological Department. Disastrous weather events 1982. A report. O/O the Additional director of meteorology, Pune. 1982;1-35.
10. Govt. of Himachal Pradesh. Memorandum of damages due to heavy snowfall, snow avalanches, hailstorm and landslides during winter season – 2019; Revenue Dept., Disaster Management Cell. 2019;1-77.
11. Govt of Himachal Pradesh. Avalanche Hazard Risk Assessment Composite Final Draft Report, (T6). Disaster Management Cell, Department of Revenue, Prepared by; TARU Leading Edge Pvt. Ltd. 2015;1-13.

12. Podolskiy E, Nishimura K, Abe O, Chernous P. Earthquake-induced snow avalanches: I. Historical case studies. *Journal of Glaciology*. 2010;56(197):431-446.
DOI: 10.3189/002214310792447815
13. Heck M, Hobiger M, Herwijnen A, Schweizer J, Fäh D. Localization of seismic events produced by avalanches using multiple signal classification, *Geophysical J. Int.* 2019;216(1):201–217.
Available:<https://doi.org/10.1093/gji/ggy394>
14. National Disaster Management Guidelines Management of Landslides and Snow Avalanches, 2009. A publication of the National Disaster Management Authority, Government of India, New Delhi; 2009.
15. Bilham R. Himalayan earthquakes: A review of historical seismicity and early 21st century slip potential. Geological Society, London, Special Publications, 2019;483:423-482.
Available:<https://doi.org/10.1144/SP483.16>
16. Gahalaut VK. Great and major earthquakes in the Himalayan Arc. *J Geol Soc India*. 2021;97:1327–1330.
Available:<https://doi.org/10.1007/s12594-021-1870-4>
17. Strapazzon G, Schweizer J, Chiambretti I, Brodmann Maeder M, Brugger H and Zafren K. Effects of climate change on avalanche accidents and survival. *Front. Physiol.* 2021;12:639433.
DOI: 10.3389/fphys.2021.639433
18. Giacona F, Eckert N, Corona C, Mainieri R, Morin S, Stoffel M, Martin B, Naaim M. Upslope migration of snow avalanches in a warming climate. *Proc Natl Acad Sci USA*. 2021;118(44):e2107306118.
DOI: 10.1073/pnas.2107306118
19. Brugger H, Durrer B, Adler-Kastner L, Falk M, Tschirky F. Field management of avalanche victims. *Resuscitation*. 2001;51: 7–15.
DOI: 10.1016/s0300-9572(01)00383-5
20. Statham G, Haegeli P, Greene E, Brickland K, et al. A conceptual model of avalanche hazard. *Nat Haz*. 2018;90:663–691.
DOI.org/10.1007/s11069-017-3070-5
21. Strapazzon G, Brugger H. On-site treatment of snow avalanche victims: from bench to mountainside. *High Alt. Med. Biol.* 2018;19:307–315.
DOI: 10.1089/ham.2018.0036
22. Wang HE, Callaway CW, Peitzman AB, Tisherman SA. Admission Hypothermia and outcome after major trauma. *Crit. Care Med*. 2005;33:1296–1301.
DOI:10.1097/01.CCM.0000165965.31895.80
23. Zafren K, Brants A, Tabner K, Nyberg A, Pun M, Basnyat B, Brodmann Maeder M. Wilderness mass casualty incident (MCI): Rescue chain after avalanche at Everest base camp (EBC) in 2015. *Wilderness Environ. Med*. 2018;29:401–410.
DOI: 10.1016/j.wem.2018.03.007
24. Oshiro K, Tanioka Y, Schweizer J, Zafren K, Brugger H, Paal P. Prevention of hypothermia in the aftermath of natural disasters in areas at risk of avalanches, earthquakes, tsunamis and floods. *Int J Environ Res Public Health*. 2022;19(3): 1098.
DOI: 10.3390/ijerph19031098.
25. Jain Neha. Warmer winters increasing risk of avalanches in the Himalayas. Published on 4 May 2018 Mongabay, scientific Magazine; 2018.
26. Sinickas A, Jamieson B, Maes MA. Snow avalanches in western Canada: investigating change in occurrence rates and implications for risk assessment and mitigation, *Structure and Infrastructure Engineering*. 2016;12(4):490-498.
DOI: 10.1080/15732479.2015.1020495
27. Singh KK, Singh DK, Thakur NK, Dewali SK, Negi KHS, et al. Detection and mapping of snow avalanche debris from Western Himalaya, India using RS satellite images, *Geocarto Int.*; 2020.
DOI: 10.1080/10106049.2020.1762762
28. Thind PS, Chandel KK, Sharma SK, Mandal TK, John S. Light-absorbing impurities in snow of the Indian Western Himalayas: Impact on snow albedo, radiative forcing, and enhanced melting. *Env. Sci Pollut Res Int*. 2019;26(8):7566-7578.
DOI: 10.1007/s11356-019-04183-5
29. Singh DK, Mishra VD, Gusain HS, Singh, et al. Simulation and analysis of a snow avalanche accident in lower Western Himalaya, India. *J Indian Soc Remote Sens*. 2020;48:1555–1565.
DOI.org/10.1007/s12524-020-01178-5
30. Puzrin AM, Thierry F, Itai E. The mechanism of delayed release in earthquake-induced avalanches *Proc. R. Soc*. 2019;A.47520190092.
Available:<http://doi.org/10.1098/rspa.2019.0092>
31. Alean J. Ice avalanches: Some empirical information about their formation and

- reach. *Journal of Glaciology*. 1985; 31(109):324-333.
DOI: 10.3189/S0022143000006663
32. Mandal J, Narwal S, Gupte SS. Back analysis of failed slopes – a case study. *Int J Eng Res Technol (IJERT)*. 2017;6(5): 1070–1078.
 33. Meena SR, Chauhan A, Bhuyan K, Singh RP. Chamoli disaster: Pronounced changes in water quality and flood plains using Sentinel data. *Env. Earth Sci*. 2021; 80(17):1–13.
 34. Mondal SK, Bharti R. Glacial burst triggered by triangular wedge collapse: A study from Trisul Mountain near Ronti glacier valley, *Geomatics, Natural Hazards and Risk*. 2022;13(1):830-853.
DOI: 10.1080/19475705.2022.2042402
 35. Li X, Sovilla B, Jiang C, et al. Three-dimensional and real-scale modeling of flow regimes in dense snow avalanches. *Landslides*. 2021;18:3393–3406.
Available:https://doi.org/10.1007/s10346-021-01692-8
 36. Waitt RB Jr, Pierson TC, Macleod NS, Janda RJ, Voight B, Holcomb RT. Eruption-triggered avalanche, flood, and lahar at mount st. Helens--effects of winter snowpack. *Sc*. 1983;221(4618): 1394-7.
DOI: 10.1126/science.221.4618.1394.
 37. Sanders D, Widera L, Ostermann M. Two-layer scree/snow-avalanche triggered by rockfall (Eastern Alps): Significance for sedimentology of scree slopes. *Sedimentology*. 2014;61:996-1030.
Available:https://doi.org/10.1111/sed.12083
 38. Ha G, Wu Z, Liu F. Late quaternary vertical slip rates along the southern Yadong-Gulu Rift, Southern Tibetan Plateau. *Tectonophysics*. 2019;755:75–90.
DOI: 10.1016/j.tecto.2019.02.014
 39. Ha G, Liu F, Cai M, Pei J, Yao X, Li L. Radiocarbon dating of the nyixoi chongco rock avalanche, southern tibet: Search for signals of seismic shaking and hydroclimatic event. *Earth Sci.*; 2022.
DOI.org/10.3389/feart.2021.793460.
 40. Chaudhary P, Bawa KS. Local perceptions of climate change validated by scientific evidence in the Himalayas, *Biol. Lett*. 2011;7767–770.
Available:http://doi.org/10.1098/rsbl.2011.0269
 41. Wester P, Mishra A, Mukherji A, Shrestha AB. The Hindu Kush Himalaya Assessment. *Mountains, Climate Change, Sustainability and People*. Cham, Switzerland: Springer Nature. 2019;627.
 42. Yang J, He Q, Liu Y. Winter–spring prediction of snow avalanche susceptibility using optimisation multi-source heterogeneous factors in the western Tianshan mountains, China. *Remote Sensing*. 2022; 14(6):1340.
Available:https://doi.org/10.3390/rs14061340
 43. Kanwar N, Kuniyal JC. Vulnerability assessment of forest ecosystems focusing on climate change, hazards and anthropogenic pressures in the cold desert of Kinnaur district, northwestern Indian Himalaya. *J Earth Syst Sci*. 2022;131:51.
Available:https://doi.org/10.1007/s12040-021-01775-z
 44. Attri SD, Tyagi Ajit. Climate profile of India. *Met Monograph No. Env. Meteorology-01/2010, IMD, MoES*. 2010;10.
 45. McClung D, Schaerer P. *The avalanche handbook: Published by the mountaineers 1001 SW Klickitat Way, Seattle, and Washington 98134*. 1993;17-18.
 46. Sharma SS, Ganju A. Complexities of avalanche forecasting in Western Himalaya — an overview. *Cold Regions Science and Technology*. 1998;31:95-102.
 47. Laxton SC, Smith DJ. Dendrochronological reconstruction of snow avalanche activity in the Lahul Himalaya, Northern India; 2008.
 48. Singh DK, Mishra VD, Gusain HS. Simulation and analysis of a snow avalanche accident in lower Western Himalaya, India. *J Indian Soc Remote Sens*. 2020;48:1555–1565.
Available:https://doi.org/10.1007/s12524-020-01178-5
 49. Dimri AP. The transport of mass, heat and moisture over Western Himalayas during winter season. *Theor. Appl. Climatol*. 2007;90:49-63.
 50. Naresh Ku, Yadav BP, Gahlot S, Singh MM. Winter frequency of western disturbances and precipitation indices over Himachal Pradesh, India: 1977-2007. *Atmósfera*. 2015;28(1):63-70.
 51. Mishra SP. Catastrophism and uniformitarianism in decision making of meghalayan age in East India. *Int. Journal of Environment and Climate Change*, 2022;12(4):19-37.
DOI: 10.9734/IJECC/2022/v12i43065
 52. Dimri AP, Palazzi E, Daloz AS. Elevation dependent precipitation and temperature

- changes over Indian Himalayan region, *Climate Dynamics*; 2022.
DOI: 10.1007/s00382-021-06113-z
53. Nayak Ramesh. SASE develops new technology to predict avalanches in western Himalayas. *India Today*; 2005.
54. Singh A, Ganju A. Earthquakes and avalanches in western Himalaya. Conference: 12th symposium on earthquake engineering (12SEE-2002); 2002.
55. Singh A, Srinivasan K, Ganju A. Avalanche forecast using numerical weather prediction in Indian Himalaya. *Cold Regions Science and Technology*; 2005.
DOI.org/10.1016/j.coldregions.2005.05.009
56. Mishra SP, Puhan JP, Mishra S. Probing the crisis of regional connectivity instigated by the natural disasters, Mizoram, India. *Int. J. of Env. and Climate Change* 2021; 11(5):39-59.
DOI: 10.9734/IJECC/2021/v11i530406
57. Hao J, Mind'je R, Liu Y, Huang F, et al. Characteristics and hazards of different snow avalanche types in a continental snow climate region in the Central Tianshan Mountains. *J. Arid Land*. 2021; 13:317–331.
DOI.org/10.1007/s40333-021-0058-5
58. Bodaballa NK, Biswas S, Roy S. Correlation between avalanches and emitted energies during fracture with a variable stress release range. *Front. Phys*. 2022;10:768853.
DOI: 10.3389/fphy.2022.768853
59. Das I, Stein A, Kerle N, et al. Probabilistic landslide hazard assessment using homogeneous susceptible units (HSU) along a national highway corridor in the northern Himalayas, India. *Landslides* 2011;8:293–308.
Available:https://doi.org/10.1007/s10346-011-0257-9
60. Muhammad S, Tian L, Nüsser M. No significant mass loss in the glaciers of Astore Basin (North-Western Himalaya), between 1999 and 2016. *Journal of Glaciology*. 2019;65(250):270-278.
DOI: 10.1017/jog.2019.5
61. Shugar DH, Jacquemart M, Shean D, Bhushan S, Upadhyay K, et al. A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. *Science*. 2021;16:373(6552):300-306.
DOI: 10.1126/science.abh4455
62. Dematteis N, Giordan D, Troilo F, Wrzesniak A, Godone D. Ten-Year monitoring of the *Grandes jorasses* glaciers kinematics, limits, potentialities, and possible applications of different monitoring systems. *Remote Sensing*. 2021;13(15):3005.
Available:https://doi.org/10.3390/rs13153005
63. Tewari VP, Verma RK, von Gadow K. Climate change effects in the Western Himalayan ecosystems of India: evidence and strategies. *For. Ecosyst*. 2017;4(13).
Available:https://doi.org/10.1186/s40663-017-0100-4
64. Bob Yirka. Global warming found to be causing an increase in snow avalanches in Western Himalayas, Physics org, report, 14 March 2018; 2018.
65. Pandita S, Kumar V, Dutt HC. Environmental variables vis-a-vis distribution of herbaceous tracheophytes on northern sub-slopes in Western Himalayan ecotone. *Ecol Process*. 2019;8:45.
Available:https://doi.org/10.1186/s13717-019-0200-x
66. Khatiwada D, Dahal RK. Rockfall hazard in the Imja Glacial Lake, eastern Nepal. *Geoenviron Disasters*. 2020;7:29.
Available:https://doi.org/10.1186/s40677-020-00165-9
67. Yriyan P, Avand M, Abbaspour RA, Karami M, Tiefenbacher JP. GIS-based spatial modeling of snow avalanches using four novel ensemble models. *The Science of the Total Environment*. 2020;745:141008.
DOI: 10.1016/j.scitotenv.2020.141008
68. Altaweel M. Forecasting and mitigating avalanches using GIS. *Spatial analysis*, 25 Oct. 2020, GIS Lounge; 2020.

© 2022 Mishra and Samal; This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:
The peer review history for this paper can be accessed here:
<https://www.sdiarticle5.com/review-history/86672>