A new approach to avalanche prediction over Indian Western Himalaya

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Avalanche prediction is mainly done by conventional and statistical techniques and over Indian Himalayas it is predicted in terms of none, low, medium and high avalanche danger as well as occurrence or non-occurrence of avalanche. In the present study, a quantitative range is calculated for each of the danger levels. Initially, normalized snow and meteorological parameters have been divided into 10 equal ranges (between 0 and 1) and an index of avalanche (IA) has been calculated for each range of every parameter. The model output has been compared with avalanches occurring over the concerned regions for the winter of 2004–05. The avalanche prediction accuracy for different regions in Lower Himalayan zone varies from 80% to 88% except at Dhundee where it is 64%. In Middle Himalayan zone, prediction accuracy on Drass is 88% and that on Patseo is 66%. It has also been concluded that the contribution of individual forecasting variables towards avalanches in different regions vary.

Keywords: Conventional technique, forecasting variables, index of avalanche.

AVALANCHE prediction over NW Himalayas has been a tedious task because of complexity of topography and diversity of the snow climate. The snow climate of NW Himalayas has been divided into three snow climatic zones – lower, middle and upper[1]. The climate of lower and middle Himalayan zone compares well with the maritime and continental while that of upper zone is close to the polar region. In the Himalayan region, classification of an avalanche on the basis of slide type, magnitude and frequency seems a tedious task because of inaccessibility of the failure zone and infrequent avalanche activities. Therefore avalanche activity over Himalaya is classified in terms of different levels of danger that are based on the dimension of the avalanche and its potential for hazard.

A number of techniques are being used to predict avalanches utilizing historical weather and avalanche data. These include discriminant analysis, cluster analysis, nearest neighbours and binary decision trees. Obled and Good[2] have presented an overview and comparison of the first three methods, Buser[3,4] detail the nearest neighbour method, and Davis et al.[5] present an example of binary decision trees.

In the present communication, an avalanche forecasting model has been developed for the application on dif-ferent road axes over NW Himalaya. The model predicts natural avalanches in terms of various levels of avalanche danger over different regions of Lower and Middle Himalayan zones. The technique used in this study to discriminate different levels of danger is not similar to those used by Bois and others[6], Bovis[7], and Obled and Good[2] because of the complexity of terrain and weather pattern over Himalayas. They developed a discriminant function based on magnitude and frequency of avalanching as well as stratification of prediction for dry and moist-wet avalanches. The discriminant function used in this study is the weighted average of index of avalanche (IA) values of the corresponding forecasting variables. This analysis differs from the past attempts in two ways: (i) the avalanche activities have been quantified according to the warnings issued on the basis of experts studies and (ii) the weights of forecasting variables vary from one region to the other.

Data used in this study have been taken from seven principal observatories (Figure 1) of Snow and Avalanche Study Establishment (SASE) functioning in different regions of Lower and Middle Himalayan zones (climatology of these zones is summarized in Table 1) and are representative of the corresponding regions and neighbouring avalanche sites of similar topography. The database consists of 11 snow and meteorological parameters (maximum temperature, minimum temperature, ambient temperature, pressure change in 24 h, average wind speed in 24 h, relative humidity, fresh snow in 24 and 48 h, fresh snow water equivalent, standing snow and sunshine hours), avalanche warning and avalanche occur-

Figure 1. Observatory network of SASE in different snow climatic zones of Himalaya.

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Table 1. Terrain and meteorological characteristics of the climatic zones of Himalaya

Snow climatic zones of Himalaya	Altitude (m)	Slope (degree)	Aspect	Ground cover	Snowfall during major storms (cm)	Highest maximum temperature (°C)	Lowest minimum temperature (°C)
Lower Himalayan zone	3200–4100 (76%)	30–38 (64%)	SE–SW (63%)	Tall grassy, forested, bushes	20–80 (56%), 80–200 (30%)	20	−12
Middle Himalayan zone	3500–5300	32–40 (75%)	SE–SW (58%)	Scree, boulders	20–80 (81%)	14.5	−25
Upper Himalayan zone	5000–5600	28–32 (67%)	NW (42%)	Rocky and glacial	10–20 (51%)	9	−40

Table 2. Weight assigned to avalanche activities taking place during different levels of danger

	Weight assigned to avalanche activity during a danger warning in different regions (AOI)			
Axis/region	None	Low	Medium	High
Stage-II	1.2	1.8	2.3	2.6
Drass	1.0	1.20	1.60	2.0
Kanzalwan	0.95	1.5	1.8	2.5
Pharkiyan	0.70	1.20	1.50	2.0
Z-Gali	0.53	0.72	0.90	0.95
Dhundee	0.03	0.07	0.11	0.17
Patseo	0.42	0.61	0.95	1.49

Table 3. Critical ranges for different levels of danger in different regions

	Critical range for different levels of danger			
Axis/region	None	Low	Medium	High
Stage-II	< 0.15	0.15 to 0.23	0.23 to 0.30	≥ 0.30
Drass	< 0.12	0.12 to 0.18	0.18 to 0.21	≥ 0.21
Kanzalwan	< 0.12	0.12 to 0.18	0.18 to 0.26	≥ 0.26
Pharkiyan	< 0.10	0.10 to 0.16	0.16 to 0.25	≥ 0.25
Z-Gali	< 0.06	0.06 to 0.10	0.10 to 0.14	≥ 0.14
Dhundee	< 0.05	0.05 to 0.09	0.09 to 0.14	≥ 0.14
Patseo	< 0.05	0.05 to 0.07	0.07 to 0.11	≥ 0.11

rence data of the past 12 winters (from 1993 to 2004) for the month of December, January, February and March. The forecasting variables recorded in the forenoon and avalanche activities during next 24 h have been taken to deliver avalanche warning for 24 h in advance. Some of the variables like maximum temperature and sunshine hours are recorded in the afternoon and therefore these variables are analysed using observations from the previous day. Database of 12 winters (1993 to 2004) have been used for developing the model and database of the winter of 2004–05 used for validation of the model. To predict avalanche activities over Lower Himalayan zone, the forecasting variables have been taken from the following representative observatories on different regions: Stage II (2650 m), Kanzalwan (2440 m), Z-Gali (3192 m), Pharkiyan (2960 m) and Dhundee (3050 m). Avalanche prediction over Middle Himalayan zone has been done by analysing the data of the observatories at Drass (3250 m) and Patseo (3800 m). Snow, meteorological and derived data with their units have been listed in Table 1.

The database has been normalized by using the relation:

$$X_{\text{Normalized}} = (X - X_{\min})/(X_{\max} - X_{\min}), \quad (1)$$

where $X_{\max}$ and $X_{\min}$ represent maximum and minimum values of the parameter.

The normalized variables have been divided into 10 equal ranges (between 0 and 1) and IA has been calcu-

lated for each range of every variable by using the relation:

Index of avalanche = Number of avalanche days in a range/Total days in the range. (2)

Avalanche activities on different regions have been assigned weights by calculating linear sum of IA values corresponding to the forecasting variables for all the warning and non-warning days in the past and averaging the sum in each level of danger. These weights have been named as avalanche occurrence index (AOI) and mentioned in Table 2.

Parameters in each region have also been assigned weights depending on the correlation of the parameter with AOI for that region. This correlation analysis gives the contribution of a parameter towards avalanche activity in different regions. Finally a critical value has been calculated by using the relation:

$$\text{Critical value } f = \sum_{p=1}^{11} X_p Y_p, \quad (3)$$

where X_p is the index of avalanche for pth variable and $Y_p = W_p/\Sigma W_p$, W_p the weight assigned to pth variable.

The quantitative range for a danger level has been calculated by averaging the critical values in each level of danger in the database. The quantitative ranges for

Table 4. Weights assigned to parameters in the two climatic zones

Snow and meteorological parameters	Weight assigned to the parameters in different regions						
	Stage-II	Drass	Kanzalwan	Pharkiyan	Z-Gali	Dhundee	Patseo
Maximum temperature	0.10	0.01	0.03	0.06	0.03	0.02	0.01
Minimum temperature	0.00	0.04	0.03	0.00	0.00	0.00	0.00
Ambient temperature	0.01	0.04	0.03	0.02	0.00	0.01	0.00
Pressure change in 24 h	0.01	0.01	0.02	0.01	0.01	0.00	0.00
Average wind speed in 24 h	0.00	0.00	0.07	0.01	0.00	0.00	0.03
Relative humidity	0.12	0.02	0.09	0.10	0.11	0.03	0.01
Fresh snow in last 24 h	0.27	0.15	0.21	0.32	0.26	0.10	0.08
Fresh snow in last 48 h	0.29	0.21	0.25	0.38	0.29	0.09	0.08
Fresh snow water equivalent	0.25	0.12	0.29	0.17	0.19	0.11	0.10
Standing snow	0.16	0.10	0.12	0.18	0.14	0.08	0.07
Sunshine hours	0.13	0.03	0.05	0.12	0.08	0.03	0.03

Table 5. Model performance for winter during 2004–05

Axis/region	Parameters of the model for winter during 2004–05				
	Accuracy (%)	Bias	False alarm rate	Probability of detection	Probability of false detection
Stage-II	80	1.0	0.27	0.73	0.16
Drass	88	1.16	0.31	0.80	0.09
Kanzalwan	86	1.18	0.26	0.87	0.14
Pharkiyan	88	0.93	0.15	0.79	0.08
Z-Gali	88	1.26	0.28	0.90	0.12
Dhundee	64	2.1	0.61	0.82	0.40
Patseo	66	2.5	0.76	0.59	0.32

different danger levels in each of the regions have been summarized in Table 3.

Weights assigned to the parameters and performance of the model in the two climatic zones have been summarized in Tables 4 and 5 respectively.

It is obvious from Table 4 that minimum temperature and average wind speed in 24 h do not contribute much towards avalanche in almost every region. Thus only nine parameters significantly contribute towards avalanche activity over Lower and Middle Himalayan zone. In these climatic zones, maximum contribution towards avalanche is of fresh snow of 48 h except at Dhundee and Patseo. At Dhundee and Patseo, fresh snow water equivalent has maximum contribution towards avalanche. The contribution of other parameters towards avalanche varies in different regions.

In the Lower Himalayan zone, maximum prediction accuracy of the model for the winter of 2004–05 is 88% (Table 5) and corresponding regions are Pharkiyan and Z-Gali. Though the false alarm rate for Pharkiyan (0.15) is less than that for Z-Gali (0.28) because of prediction accuracy for avalanche occurrence, i.e. probability of detection (for Pharkiyan is 79% and that for Z-Gali 90%), the model performance for Z-Gali is better than that for Pharkiyan. Keeping all the model parameters in view, the overall performance of the model is better at Kanzalwan in the Lower Himalayan zone than any other region over

the Himalayas. In the Middle Himalayan zone also, the maximum prediction accuracy is 88% for Drass. Performance of the model is poor for Patseo (66%) in Middle Himalayan zone and Dhundee (64%) in Lower Himalayan zone for the winter of 2004–05. It is because of less human activity and consequently poor and delayed feedback of avalanche activities over the region during winter.

This study infers that nine out of 11 snow and meteorological parameters have considerable contribution towards avalanche in all of the regions over north–west Himalayas. Out of these, nine contributory parameters, fresh snow of 48 h is the most dominant parameter in all the regions except at Dhundee in Lower Himalayan zone and Patseo in Middle Himalayan zone. At Dhundee and Patseo, fresh snow water equivalent has been found to be the most dominant parameter. Other parameters contribute in a variable manner in different regions. Performance of the model for winter of 2004–05 is satisfactory with highest prediction accuracy at Pharkiyan and Z-Gali (88%) in Lower Himalayan zone and Drass (88%) in the Middle Himalayan zone. Model performance for Dhundee and Patseo is poor with prediction accuracy 64% and 66% respectively. Low prediction accuracy at these regions is mainly because of less and delayed avalanche feedback. Prediction accuracy of the model can further be increased by incorporating physical processes of the snow pack into the model.

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Occurrence of small scale inflated pahoehoe lava flows in the Mandla lobe of the eastern Deccan volcanic province

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We report here emplacement of small scale inflated pahoehoe lava flows in the Mandla lobe of the Eastern Deccan Volcanic province (EDVP). These lava flows are thick and display entire range of characters similar to that occurring in the Western Deccan Volcanic Province (WDVP). Size of the lobe in these lava flows is very small and they are less in number compared to those occurring in the WDVP. Moreover, simple lava flows that occur in the younger sequences of the basalts around Mandla area, form extensive sheets and look like a lava field. Physical characteristics of Mandla lavas are suggestive of lower effusive rates, linked with the low magnitude of eruption, possibly related to its long distance migration from a common source, located in the western Deccan province.

THE Deccan Traps are continental flood basalts that record immense accumulations of tholeiitic basaltic eruptions, with an eruptive area of 1.5×10^6 sq. km (Figure 1 *a*). Most intense pulse of volcanism occurred at 66.9 ± 0.2 Ma, preceding the Cretaceous/Tertiary Boundary (KTB, 65.2 ± 0.2 Ma), approximately over a time period of 1.7 Ma (ref. 1). This is one of the largest igneous provinces in the world with a wealth of information available on its stratigraphy, structure, geochemistry, petrogenesis, age and the duration of the volcanism. The Mandla lobe forms a 900 m thick lava pile (Figure 1 *b*). More specifically, it forms an extension of the northeastern Deccan, covering an area of 29,400 sq. km. The landscape is covered by flat-topped plateaus (Maikala) and ridges that often carry small mesas and buttes. The horizontality and undisturbed nature of the flows is reflected through fairly common amphitheatrical valley heads with narrow entrances and steep sided walls. With the trap-basement contact (lava flows resting over infratrappean sediments) at 364 m asl (above sea level) near Jabalpur and maximum elevation of 1177 m asl at Badargarh Mountain near Amarkantak, the lava pile attains a thickness of ~900 m. Major topographic breaks occur at 450, 600 and 900 m asl and duricrusts of laterite often cap the plateau above the latter with bauxite deposits at places towards the eastern part.

Regional mapping and detailed petrographic studies of lava flows coupled with the lateral tracing revealed presence of 37 physically distinct lava flows[2–4] in the 900 m thick lava sequence in the Mandla lobe (Figure 1 *b*) of the eastern Deccan volcanic province. The geographical spread and the order of superposition in this outlier revealed that the older flows occur in the west of the outlier at Seoni–Jabalpur–Sahapura sector, whilst the younger flows are confined to Dindori–Amarkantak sector at the east. Considering the megascopic and microscopic characters and the best exposed localities, nomenclature was proposed for 37 lava flows[2,3]. The Dhanwahi plagiophyric (Flow 4), Kahani giant clinopyroxene basalt (Flow 8), Surjitolla columnar (Flow 11), Rehtapakri columnar (Flow 17), Sahapura plagiophyric (Flow 21) and Murgatolla coarse-grained (Flow 23) lava flows have wide spatial spread (Figure 1 *b*), ranging from 50 to 100 km along A–B, B–C and D–E traverses (figures 4a, b and c; ref. 3). Their megascopic characters, micropetrography and wide geographic spread favour their usage as marker horizons in the Mandla lobe of the Eastern Deccan Volcanic Province (EDVP). The major-oxide chemistry of the sampled flows justifies the presence of 37 lava flows and their physical correlation across the measured sections.

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