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Variation in snow cover density — A pilot study

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ABSTRACT. Observations of snow cover recorded at three stations in snow bound areas of northwest Kashmir for the period 1973-77 have been analysed with the aim to bring out (*i*) variability of fresh snow density with ambient temperature and time and its effect on water equivalent and (*ii*) variability of snow cover density with depth, slope orientation and different winter months.

1. Introduction

All the rivers originating from the Himalayas are snow and glacier fed. Table 1 gives the average monthly discharge values (cusec) recorded in *Sutlej* river at Bhakra over a period of 47 years from 1925-71. A sudden increase in the mean discharge from April onward may be attributed to the contribution of snowmelt runoff, as during the pre-monsoon months (April-June) the Sutlej catchment does not receive enough rainfall.

It is, therefore, important to estimate the water potential from seasonal snow cover, as its contribution to the inflows of all the rivers originating from the Himalayas is highly significant from April to June/July. The total water equivalent of snow cover depends upon (*i*) surface area of the snow cover, (*ii*) its depth and (*iii*) average density. Satellite imageries and other remote sensing techniques are providing a real extent of snow cover over a catchment periodically. Snow depth observations are also possible by gamma-ray techniques. But for estimating the density of snow cover we have to depend upon manual observations till a reliable sensor for the same is developed successfully. The aim of this study is to bring out the variability in densities of fresh and seasonal snow cover with respect to time, space, slope orientation and other related parameters.

2. Characteristics of snow

A snow crystal consists of ice, air and water; ice forming the framework with air and water filling up the voids. A snow cover may be regarded as the sheet of such crystals randomly arranged and intercommunicable with one another. The density of a snow sample depends on the void ratio or porosity (p) of the crystals, which is defined as :

$$p = (1 - \rho_s/\rho_i) \times 100 \qquad (1)$$

where,

ρ_s density of the snow sample, and

ρ_i density of hard ice (0.917 gm cm^{-3}).

The porosity of hard ice is zero, whereas in a dry snow the void ratio may be more than 95 per cent. The porosity and hence the density is a function of the type of crystals which depends on the manner in which the vapour molecules are deposited around ice nuclei in a cloud mass above freezing level. As quoted by Collins (1966), an American Scientist Bentely photographed about 6000 different types of crystals in his life-time and yet felt the list was incomplete. Densities of some important types of crystals as mentioned in *Avalanche Hand Book* (1978) are given below :

Types of crystals	*Density (gm/cm³)*
Dry flakes	.03 .05
Loose dry snow	.05 -.09
Wind packed snow	.12 -.30
Round or irregular grains	.24 -.43
Cup crystals and depth hoar	.15 -.38
Wet snow	.50 -.83
Soft ice	.834
Hard ice	.917

TABLE 1

Average monthly discharge of the *Sutlej* at Bhakra (Period 1925-1971)

Month	Average discharge (cusec)	Month	Average discharge (cusec)
Jan	4345	Jul	49149
Feb	4431	Aug	52213
Mar	4760	Sep	24596
Apr	6676	Oct	9957
May	18336	Nov	5880
Jun	30304	Dec	4575

TABLE 2

Year	Dec	Jan	Feb	Mar	Apr
Station A (ht 2410 m)					
1973-74	.095	.084	.042	.067	.165
1974-75	.067	.059	.051	.116	.197
1975-76	.063	.077	.081	.092	.250
1976-77	.065	.072	.059	—	—
Mean (gm/cm³)	.073	.073	.058	.092	.204
Station B (ht 3128 m)					
1973-74	.100	.125	.110	.160	.180
1974-75	.118	.128	.100	.240	—
1975-76	.090	.100	.090	.130	—
1976-77	—	.055	.055	—	—
Mean	.103	.102	.089	.177	.180
Station C (ht 3080 m)					
1973-74	.089	.084	.100	.168	—
1974-75	.080	.062	.061	.169	—
1975-76	.070	.110	.110	.150	—
1976-77	.065	.054	.055	—	—
Mean	.076	.077	.081	.162	—

3. Water equivalent of snow

The depth of water obtained by melting the whole snow cover on the same area, assuming that there are no losses due to evaporation, infiltration or runoff, is termed as the water equivalent of the snow cover. The water equivalent (W) of a snow cover of thickness D is given by

$$W = \sum_{i=1}^{n} d_i \rho_i = \bar{\rho} D \tag{2}$$

where, the snow cover of thickness D has been divided into n homogeneous thicknesses $d_1, d_2, \ldots \ldots \ldots \ldots d_n$ having densities $\rho_1, \rho_2 \ldots \ldots \rho_n$ respectively. The mean density of snow cover $\bar{\rho}$ may be defined as :

$$\bar{\rho} = 1/D \sum_{i=1}^{n} \rho_i d_i \tag{3}$$

It is customary for Indian snowfall regions to assume a constant value of fresh snow density as 0.1 gm/c c and hence the water equivalent of snow is one tenth of snowfall depth. Seeing the large variations in snowfall densities, this thumb rule may not be appropriate particularly during early winter when $\rho < 0.1$ and late winter periods when $\rho > 0.1$ and may give misleading results. For estimating exact amount of water equivalent, density of fresh snow is required to be measured. This may be done in a simple way by weighing a small cylinder full of snow whose volume is known (generally 1000 c c). In case it is not possible to arrange these apparatus for each observatory the thumb rule may be modified by using appropriate densities for each month. It may be mentioned here that the accuracy of snowfall observations in terms of water equivalent recorded by cylindrical snowgauges also is not very high for the want of representative sample collection. Winds and intensity of precipitation in mountain regions tend to reduce this accuracy. It is felt that the density and snow depth method of water equivalent is more reliable.

4. Variation in fresh snowfall density

Fresh snowfall densities were recorded at 3 stations A, B and C in avalanche prone regions of northwest Kashmir. These stations are situated at various altitudes, *viz.*, A (34°35′N, 74°40′E, 2410m); B (34°25′N, 75°50′E; 3128m) and (34°25′ N, 75°10′E; 3080m). Monthly mean densities (gm cm^{-3}) at these places over a period (1973-1977) are given in Table 2.

It has been observed that the density of fresh snow follows the variation trend of ambient temperature to a considerable extent. On occasions and places of lower ambient temperatures the snow crystals have been found dry or less humid and with lower densities. During February, when the snow density was low the temperature was also observed to be minimum during the same period. Thus the behaviour of minimum temperature during a snow spell is a very important factor for estimating its water equivalent.

In order to establish a relation between fresh snowfall density (ρ gm cm^{-3}), and ambient temp (T deg. C), 3 different samples were studied. The scatter diagrams suggested a linear relationship between the two. The linear regression equations between ρ and T have been worked out and are given below :

Station A : $\rho_1 = 0.123 + 0.005T$
Station B : $\rho_2 = 0.107 + 0.003\ T$
Station C : $\rho_3 = 0.117 + 0.008\ T$,

where, ρ is in gm/c c & T is in centigrade.

The gradients of these lines are highly significant.

5. Variation of snow cover density

If a snow cover has uniform texture, its density increases with depth for the simple reason that the lower layers are compressed by the weight

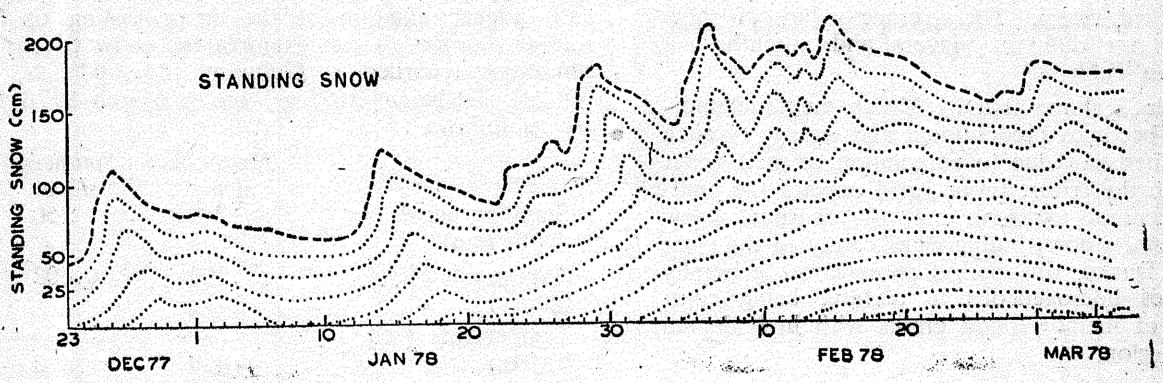

Fig. 1

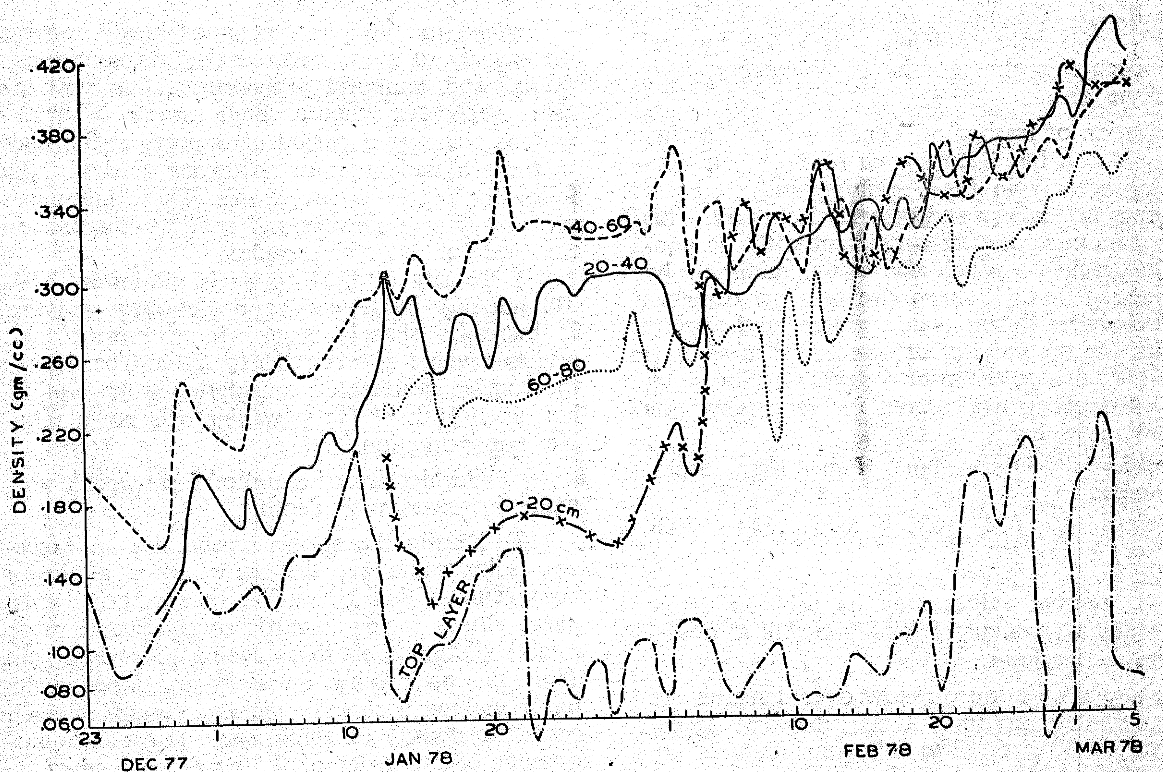

Fig. 2

TABLE 3

Average density (gm/cm³) and temp. (°C) of snow cover

Snow depth	January		February		March	
	ρ	T(°C)	ρ	T (°C)	ρ	T (°C)
60-Top	0.092	—7.2	0.090	—8.1	0.150	—3.8
40-60	0.240	—5.3	0.270	—4.8	0.350	—2.6
20-40	0.290	—4.4	0.288	—4.2	0.380	—2.3
0-20	0.329	—1.9	0.330	—1.7	0.380	—1.3
Mean	0.238	—4.7	0.245	—4.7	0.320	—2.5

of the above layers. As an example snow density recorded at various depths of snow cover at Gulmarg on 28 February 1976 are presented below :

Depth of snow cover (cm)	*Density (gm/cc)*
0	.120
50	.205
80	.235
110	.315
148(ground level)	.330

A sample study of variation of snow density with depth was carried out at stations under consideration during the winter of 1978 by observing densities at various layers of the snow cover every day. For this a pit was dug in the snow cover every day and snow samples were collected in each layer of 20 cm interval in a cylindrical vessel. The average values of snow density for different layers and months are given in Table 3.

Table 3 shows that by March melt metamorphism becomes predominant and density of each layer increases due to percolation of melt water through the cover. From April onward the melting becomes excessive and the seasonal snow cover starts contributing significantly to the river flows. During this period snow cover generally becomes homogeneous in texture, being composed of mainly round grains with high degree of cohesion.

6. Time variation of snow cover density

Snowfall in Western Himalayas generally takes place during the month of December to April, though at reaches higher than 3.0 km asl snow occurs in the months of November, May and June also .

Variation of fresh snow densities from December to March has been shown in Fig. 1. It decreases gradually in the beginning and attains a minimum in January end or early February. This phenomenon is fairly in agreement with the temperature variation which also attains minimum by the same period. A sharp rise in snow densities are observed during late winter and spring months. On the basis of data recorded at stations A, B & C during the past 4 years the following means have been worked out for various months in Kashmir valley :

Months	Dec	Jan	Feb	Mar	Apr
Average densities (gm/cc)	.084	.083	.076	.144	.192

These normal values may be used to determine water equivalent of fresh snowfall at observatories in Kashmir.

A sample variation of snowcover densities are also presented in Fig. 2 for different layers (ground to 80 cm). The following features are observed from Figs. 1 and 2 :—

(*i*) In all layers the variation in density exhibits increasing trend with the advancement of season. It may be regarded mainly due to pressure metamorphism which continues to increase with time owing to faster growth of standing snow depth.

(*ii*) The variations in densities of different layers reduces in late winter or spring months. In other words the cover tend to acquire uniformity with respect to density in later part of the winter. From March onwards the cover becomes fairly uniform except for the topmost layers which remain lighter due to fresh snowfall or comparatively less settled snow.

(*iii*) On slopes facing towards the south in Western Himalayas the melt metamorphism is more predominant than on northern slopes. It causes faster settlement, faster homogenisation and quicker ablation of the cover resting on southern slopes. As an example the snow cover conditions recorded at Gulmarg (34° 03′ N, 74° 24′ E; height 2655 m) on 18 March 1978 are as follows :

	Northern slopes	*Southern slopes*
Standing snow depth (cm)	240	150
Average density (gm/cc)	.300	0.402
Temperature (°C)		
(*i*) Top	—4.0	0.0
(*ii*) Average	—0.5	0.0

7. Summary and conclusions

Owing to various metamorphism process the density of snow cover undergoes continuous spatial and temporal variations. After studying these variations from a small sample of observations covering a period of 4 years at 3 places in snow bound areas of northwest Kashmir, the following inferences are drawn. These inferences are tentative at present and need verification on the basis of a larger sample.

(*i*) Density of fresh snow is minimum (.06-.08 gm/cc) in January and February months. It increases sharply from March onward and attains a value between .15 to .20 gm/cc. Hence the routine practice of considering water-equivalent as 1/10th of the snow depth is not a reliable approximation.

(*ii*) The density of a uniform snowpack normally increases with depth.

(*iii*) During the spring season due to excessive solar radiation, the snow cover attains a homogeneous density profile. In northern hemisphere slopes facing towards south receive more solar radiation than those facing towards north. Thus the pack lying on southern slopes melts faster making it ripe for yielding runoff. In such cases the density of whole snow cover is homogeneous of the order of 0.5 or 0.6 gm cm^{-3}

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