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Snowmelt processes and applications

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सार—हिम एक ऐसा परिवर्तनशील द्रव्य है जिसकी संरचना और गुणों में लगभग निरन्तर ही परिवर्तन होता रहता है। इस विलक्षण पहलु के अलावा, जल आपूर्ति, मनोरंजन, पर्यावरण मानकों के अनुरक्षण, वायुमण्डलीय परिसंचरण के संशोधन, हिमनद एवं हिमस्खलन जैसे विनाशकारी बलों में हिम की भूमिका विचारणीय है। प्रस्तुत शोध पत्र में इस विषय के निम्न तीन पहलुओं पर विचार किया गया है :—

(1) हिम सम्बन्धी परिघटना के गुणधर्मों को स्पष्ट करते हुए विशेष आंकड़ों और सूचना का प्रस्तुतीकरण किया गया है। ये सूचनाएं लेखक ने स्थलीय प्रेक्षणों सहित विभिन्न पुस्तकों और अन्य सामग्रियों से एकत्रित की हैं।

(2) निम्नलिखित अध्ययनों की कार्यपद्धति और उनके परिणामों का प्रस्तुतीकरण किया गया है :—

(क) ऊष्मा स्थानांतरण के समीकरण के उपयोग से हिम तह की ऊष्मीय-संरचना का निगमन।

(ख) समय और क्षेत्र के संदर्भ में घनत्व परिवर्तन।

(ग) हिम पिघलने सम्बन्धी प्रक्रियाएं।

(3) कुछ समस्याओं की पहचान और भविष्य में किए जाने वाले अध्ययनों के प्रस्ताव की रूपरेखा का प्रस्तुतीकरण भी किया गया है।

ABSTRACT. Snow is a dynamic material which changes its texure and properties almost continuously. Besides this challenging aspect, we are also concerned with its rõle in water supply, recreation, maintenance of environmental standard, modifying atmospheric circulation and also in destructive forces like avalanche and slides. Present paper deals with following 3 aspects of this subject :

(*i*) Presentation of specific data and information illustrating properties of snow related phenomena. These informations have been collected from various literature and other materials including field observations collected by the author.

(*ii*) Presentation of methodology and results of the following studies :

(a) deduction of thermal structure of snowpack using equation of heat transfer,

(b) density variations in time and space, and .

(c) snowmelt processes.

(*iii*) Identification of some problems and outlining the proposal for further studies.

Key words — Glacier, Baroclinicity, Snowmelt, Snowline, Insolation, Density, Parameterization.

1. Introduction

Annually, India receives about 4000 km^3 of water through precipatation; 95% from rain and 5% from snow and glacier melt. While rain is good producer of fresh water, it is very poor distributor. The distribution is concentrated only in a few months of monsoon and in some parts of the country; thus resulting into floods and droughts. On the other hand, snowmelt is a poor producer but good distributor of fresh water as it regulates runoff of north Indian rivers during lean period of summer.

Snowcover also affects weather and climate. Among its large scale effects are—inverse radiative tropospheric cooling, formation of cold airmass and pressure systems. Small scale effects are—generation of baroclinicity at the interface of snow and bare ground, stability of adjacent air and production of local wind patterns.

Paper deals with some of the processes in snow and glacier in relation to the above mentioned influences on weather and water resources.

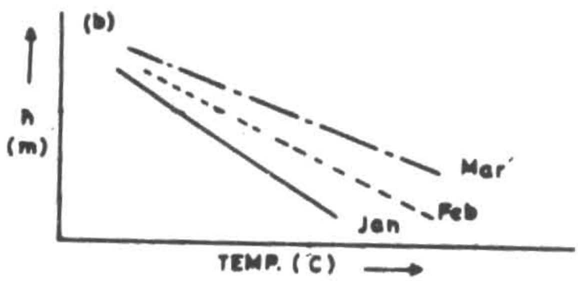
2. Modelling snowmelt processes

(*i*) Divide a snow bound catchment into various altitude zones.

Let there be n zones. The physical/meteorological inputs for these zones may be prepared as under:

Zone	Altitude range (m)	Area (km^2)	Mean temp. (°C)
1	h_0-h_1	a_1	t_1
2	h_1-h_2	a_2	t_2
I	I	I	I
I	I	.	I
I	I	I	I
I	I	I	I
n	h_{n-1}-h_n .	a_n	t_n

(*ii*) For obtaining t_i the temperature of ith subzone, establish the lapse rate of surface temperature from normal temperatures recorded at various altitudes and plot them as graph shown below:



The slope of lines represent lapse rate (r) for the given month.

If the temperature recorded at observatory (altitude h) during an expedition is t, then

$$t_i = t + (H-h_i)r.$$

(*iii*) *Computation of melt rate*

(a) *Energy balance approach*—Melt rate (M_i) from ith subzone can be expressed as:

$$M_i = Q\ (1-r) - \sigma(\varepsilon_1 T_a^4 - \varepsilon_2 T_s^4)$$

where. Q is net solar radiation incident on the surface; r is albedo: T_a and T_s are the temperature of ambient air and snow surface respectively. Usually snow is regarded as a black body: hence its emissivity $\varepsilon_2 = 1$. At the time of significant melting (during summer days)

$$T_s = 273°K.$$

Albedo of snow is highly variable. For fresh snow it ranges from 75 to 95% whereas for old snow 40 to 70%. Some researchers (U.S. Army Corps of Engrs 1956, Upadhyay *et al.* 1983) have tried to relate it with age of the snow.

Other components of energy balance, *viz.*, latent and sensible heat transfers are less important in melting snow in Himalayan ranges. Their importance increases with latitude as evident from normal energy balance figures indicated in section 4.

(b) *Temperature based degree day approach*—If T_θ is number of degree days [estimated as mean of hourly (+ve) temperatures during a day], it is possible to work out an index T_ϕ based on degree days of nth, $(n-1)$th, $(n-2)$th days etc as:

$$T_\phi = W_1\ (T_\theta)_{n-1} + W_2\ (T_\theta)_{n-2} + \ldots\ldots$$

so that $\Sigma\ W_i = 1$. Usually the weights decrease faster with the lag of days.

In U.S. Army Corps of Engrs (1956) report, the values are given as

$$W_1 = .6,\ W_2 = .3 \text{ and } W_1 = .1.$$

It is possible to relate snowmelt rate as

$$SM = KT_\phi;$$

K can be empirically/conceptually estimated. According to an estimate

$$K = .0011\rho,$$

where, ρ is snow density in kg/m^3.

(c) Melt rates from each altitude zones can be computed and pooled to an area weighted average.

3. Role of snow and glacier melt in design storm study

22 major rivers of north India originate from the Himalayas which are primarily fed by snow and glacier. Numerous sub-catchments of these rivers and their tributaries lying over the Himalayas are partly snow-bound. According to an estimate there are about 5,000 glaciers in these basins covering an area of over 33,000 km^2. During high winters (January-February), this area increases several times due to spread of seasonal snowcover. The runoff pattern of the rivers is

significantly affected during the melt period of snow. Consideration of snowcover is particularly important in computations of design floods, where, alongwith probable maximum storm, the optimum conditions of snowpack and its melt has to be taken into account. Another complication arises due to large difference in the time of residence of snow and water in the basin. Ice and snow play less active role in hydrological cycle because of their high residence time as copared to rain water.

In a snow-free catchment a design storm study consists of 5 steps, *viz.*, storm selection over the catchment or over a homogeneous zone around it; its transposition over the project area; Depth Area Duration (DAD) analysis; computation of location, barrier and moisture adjustment factors; and evaluation of critical time distribution of storm rainfall. In a snow-bound basin the quantity of melt water behaves exactly as rainfall in generating floods after being subjected to likewise losses due to evaporation, infiltration and surface retention. For evaluation of PMP, the optimum conditions of snowpack and meteorological factors including soil storage have to be considered to provide maximum water yield from snowmelt during storm period.

For snowpack condition one has to take into account its water equivalent, areal extent and structural character. Sufficient snow having minimum depth should be ideal for minimum storage loss.

For snowmelt computation in open ground, air temperature, wind and rainfall are important whereas, in forested area only air temperature and rainfall are sufficient. Optimum values of these elements should be taken during the storm period.

At the beginning of PMP storm snowcover absorbs water provided by rain and snowmelt till the pores are saturated. Thereafter, the surface runoff appears from snowpack. It is important to evaluate water equivalent of snowpack before and after the storm which can be done with the help of snow course observation.

The drainage area can be divided into various elevation zones and for each zone the quantity (Rainfall + Snowmelt — Water storage in snowpack) may be calculated for each 6-hour and 12-hour period.

Degree day methods for computation of snowmelt, as given below, may be used (Upadhyay *et al.* 1991):

$$SM = a\theta,$$

where, a is degree day factor (cm °C^{-1}day^{-1}) and θ is number of degree days, that is the average of positive temperature during 24 hours.

$$a = 1.1\rho,$$

where, ρ is average density of snow (gm/cc).

The snowmelt rate is enhanced when rain water falls over snowpack. If r cm of rain occurs over a snowpack then the quantity of snowmelt (M) due to this is given by (Upadhyay *et al.* 1990):

$$M = rT_w/80 \text{ cm.}$$

where, T_w is wet bulb temperature representing the temperature of rain water.

Some authors have also suggested empirical equations for deriving melt rates under optimum meteorological conditions. Presenting saturated air condition and a linear variation between dew point and saturation vapour pressure, the following equations computing melt rate (M—inch/day) has been suggested:

(*i*) For forested area
$$M = (.74+.007Pr)\ (T-32)+.05.$$

(*ii*) For open plain area
$$M = (.029+.0084v+.007\ Pr)\ (T-32)+.09$$

where, Pr — Rainfall (inches)
T — Air temperature (°F)
v — Wind speed (mph)

3.1. *Consideration of snow line*

In many cases the catchments are partly snow-bound. In such cases the immediate problem is to ascertain the actual area of snowcover during storm period. Area-elevation curve is generally available as a catchment characteristic. If the altitude of snow line is available either by ground observations or from satellite imageries, the areal extent can be estimated with the help of area-elevation curve.

In India PMP storms usually occur during June-October period. Seasonal snowcover melts away in this time. Hence permanent snow line or firn line is desirable. The observations in these regards are very rare. Mohan Rao (1983) studied progress of snow line in Beas catchment based on observations recorded during 1981-82. According to his observations the snow line is lowest in February (about 2000 m asl). If T = 0 for February, 1 for March, 2 for April, 3 for May, 4 for June, 5 for July, 6 for August and —1 for January, —2 for December, —3 for November, —4 for October, —5 for September, altitude of snow line (100 m) may be given as $x = 20 - .8t + t^2$.

4. Energy equation

Consider an atmospheric column standing over a unit area. Rate of change of internal energy (U_a) in this column is given by :

$$\frac{dU_a}{dt} = Q_a + (1 - \alpha)\, Q_{si} + Q_v + Q_g + Q_{le}.$$

- Q_a — Shortwave radiation flux, absorbed by the atmosphere.
- α — Albedo,
- Q_{si} — Shortwave radiation flux incident on the surface,
- Q_v — Net flux (to or from column) due to exchange of latent and sensible heat with surrounding air.
- Q_g — Net flux between column and surface of earth, and
- Q_{le} — Longwave radiation flux to space.

If $\frac{dU_a}{dt} > 0$, then ambient temperature is increasing. Approximately a change of 10^4 KJ/m² in U_a increases mean temperature by 1°C.

On annual scale $\frac{dU_a}{dt} = 0$, as there is no change in annual temperature of a place.

Mean Annual values (w/m²) of energy balance components

Latitude (°N)	Q_a	Q_{si}	$(1-\alpha)\,Q_{si}$	Q_v	Q_g	Q_{le}
20	74	231	211	-39	−4	−242
40	52	187	163	−9	14	−220
60	36	115	93	55	15	−199
80	25	83	37	108	5	−175

(i) Estimation of Q_{si} and Q_a

Insolation at the top of atmosphere depends on *(i)* time of year (declination), *(ii)* time of the day (hour angle), and *(iii)* latitude of the place. There is no interannual variation in these values. For practical use the daily values (R_0) have been computed at standard latitude for different months and provided in form of nomograms and table.

In a cloud-free atmosphere the incident radiation *(R)* on earth's surface is reduced due to atmospheric

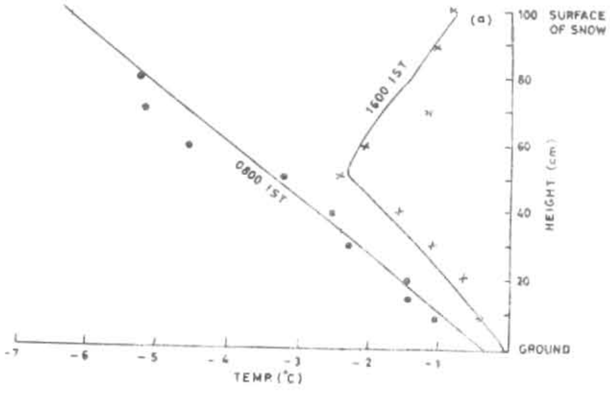


Fig. 1. Variation of snow cover temperature with depth

transparency (optical air masses). According to U.S. Army Corps of Engrs (1956).

$R = .80\ R_0$, during winter and $R = .85\ R_0$, during summer.

If N is amount of cloudiness, the net radiation (ly day^{-1}) reaching on a surface may be given as :

$$Q_{si} = [1-(0.82 - 0.000073Z)\, N]R,$$

where, N is in decimal fraction and Z is cloud height in m.

If r is the albedo of snow surface, then the *SW* radiation absorbed

$$Q = (1-r)\, Q_{si}$$

r is generally a function of : (a) age of the snow surface, (b) water content of the pack.

(ii) Estimation of Q_{le}

Net longwave input to the snow surface is given by :

$$Q_{le} = \sigma\, (\varepsilon T_a^4 - T_s^4)\, (1 - K^* N),$$

where, ε is emissivity of air. Empirical value of ε depends on surface vapour pressure (e_a) and may be given as :

e_a (hPa) :	6	9	16	25
ε :	.623	.653	.714	.775

Snow is regarded as black body ($\varepsilon = 1$).

Constant K^* depends on height of clouds such as :

For low & thick clouds	$K^* = .76$
For medium clouds	$K^* = .52$
For high clouds	$K^* = .26$

(iii) Q_v is determined using well known equation of turbulent exchange of specific humidity and temperature. This term has two components, *viz.*, latent heat (Q_e) and sensible heat (Q_c).

If U_a (ms^{-1}) is the wind speed observed at height Z_a (m), then

$$Q_e = \frac{0.622\,\rho\,L\,K_T}{p}(e_a - e_o)\,U_a$$

and

$$Q_c = \rho\,c_p K_T (T_a - T_o)\,U_a$$

where

ρ — Air density (gm cm^{-3}),
c_p — Specific heat of dry air (= 0.24 cal gm^{-1}k^{-1}).
L — Latent heat (= 677 cal gm^{-1}) for snow-vapour system, and
p — Atmospheric pressure (hPa)

e_a, e_o and T_a, T_o are vapour pressure (hPa) and temperature (°C) at levels Z_a and Z_o (snow-surface) respectively. K_T is the transfer coefficient given as :

$$K_T = \frac{K^2}{\ln^2 (Z_a/Z_o)}\left[1 - \frac{R_i}{R_c}\right]^2$$

$$R_i = \text{Bulk Richardson No.} = \frac{2gZ_a\,(T_a - T_o)}{U_a^2\,(T_a + T_o)}$$

R_c = Critical Richardson number beyond which turbulent conditions do not exist (R_c = .2 to .5)

Illustration of energy budget calculation

The input information (Upadhyay *et al.* 1983) :

(*i*) Place — Shimla (31°06′N, 77°10′E; 2202 m)

(*ii*) Date — 21 March 1993.

(*iii*) Meteorological data :

Air temp. (T_a) = 280°K at height Z_a = 1.25 m agl,

Snow surface temp. (T_o) = 273°K,

Cloudiness (N) = 0.4,

Height of cloud = 3000 m agl (Z),

R. H. = 50%, Wind speed (u_a) = 2 ms^{-1},

Albedo (r) of snow surface = .6,

Quality of snow — Smooth on grass.

Shortwave radiation (Q_{rs})

The radiation received at the top of atmosphere at latitude 31°06′N on 21 March is :

R_o = 370 Wm^{-2} = 765 ly day^{-1} (from standard table).

Incident at surface

$$Q_{si} = .8\,R_o\,[1-(.82-.000073Z)N] = 465 \text{ ly day}^{-1}$$

$$Q_{rs} = Q_{si}\,(1-r) = 186 \text{ ly day}^{-1}$$

Longwave radiation (Q_{le})

$$Q_{le} = \sigma\,(.7\,T_a^4 - T_o^4)\,(1 - K^*N), \quad K = 0.52$$
$$= 1.189\times10^{-7}\,(430.26\times10^7 - 555.46\times10^7)\,(1-.2)$$
$$= -119 \text{ ly day}^{-1}.$$

Latent heat input (Q_e)

For smooth snow on land the roughness height (Z_o) = 0.7 × 10^{-3}m.

Transfer coefficients under neutral condition

$$K_N = \frac{K^2}{\ln^2 (Z_a/Z_o)} = \frac{(.4)^2}{\ln^2\left(\frac{1.25}{.0007}\right)} = 2.85\times10^{-3}$$

Air over snow is in stable conditions.

Richadson number

$$R_i = \frac{2gZ_a\,(T_a - T_o)}{(T_a + T_o)\,U_a^2} = \frac{2\times9.8\times1.25\times7}{(280+273)\times KZ^2} = 0.077$$

$$\frac{R_i}{R_c} = .077/.2 = 0.39$$

$$K_T = 2.85\times10^{-3}(1-.39)^2 = 1.1\times10^{-3}.$$

$$\therefore E = \frac{.622\ \rho\ K_T}{p}(e_a - e_o)\ U_a$$

$$e_a = \frac{1}{2}\ (\text{SVP at } T_a = 280°\text{K}) = \frac{1}{2}\ (10.01) = 5\ \text{hPa}$$

$$e_o = \text{SVP at } 273°\text{K} = 6.1\ \text{hPa}$$

$$\rho = 1.1\times10^{-3}\ \text{gm cm}^{-3}.\ U_a = 200\ \text{cm s}^{-1}$$

$$\therefore E = \frac{.622\times1.1\times10^{-3}\times1.1\times10^{-3}\times1.1\times200}{1000}$$

$$= 1.66\times10^{-7}\text{gm cm}^{-2}\ \text{s}^{-1}$$

$$\therefore Q_e = LE = -677\times1.66\times10^{-7}\ \text{ly s}^{-1} = -9.7\ \text{ly day}^{-1}.$$

Sensible heat $Q_c = \rho\ c_p\ K_T\ (T_a - T_0)\ U_a$

$$= 1.10\times10^{-3}\times0.24\times1.1\times10^{-3}\times7\times200\ \text{ly s}^{-1}$$

$$= 35.1\ \text{ly day}^{-1}$$

$\therefore$ Energy budget (ly day^{-1}) and consequent snowmelt is given by :

Q_{rs}	Q_{rl}	Q_e	Q_c	*Total*	*Snowmelt* (cm/day)
186	—119	—10	35	+92	1.15

5. Snowcover monitoring

Network of observational sites—Snow-bound portion of a river basin usually comprises a number of sub-catchments belonging to various tributaries, *nallahs* or khuds, emerging either from underground channels or from glaciers or mountainous lakes. In all cases the basic feed comes from snowmelt; immediate or delayed. Hence a sub-catchment or a group of sub-catchments should be taken as the unit for monitoring snowcover for hydrological purposes. In a unit there may be one or more *observational* sites depending on the following factors :

(*i*) Area of the unit;

(*ii*) Characteristic features of the basin like topography; vegetation cover, exposure to sun and wind. These features should be proportionately represented in network as far as possible;

(*iii*) Purpose of observations;

(*iv*) Availability of instrumentation and physical facilities.

Due to the constraints mentioned above, it is not possible to fix up and rigid criteria for the density of observational network. However, to account for the spatial variabilities and to estimate areal parameters from point observations reasonably accurate, the following suggestions for minimum network density are made :

1. There should be one main observatory for each 1000-10,000 km² of area. It should be manned by a team of trained personnel and equipped with the instruments capable of observing most of the hydrological (discharge, snowdepth, density, stratigraphic observations etc) and meteorological (precipitation, temperature, radiation, albedo, humidity, wind etc) parameters. Sets of portable equipment and snowkits are also necessary for snow surveys and mass-balance observations.

2. Under the main observatory there should be a number of part-time or subsidiary observatories covering an area say 100-1000 km² well distributed over the watershed.

3. It is still quite possible that difficult or uninhabited terrains remain uncovered by the manned stations mentioned above due to logistic problems. But to complete the network, observations from these places are necessary. The sites of observations in these areas should be selected in advance, preferably during summer and observations can be taken by the following techniques :

(a) Installing telemetering system connecting automatic recording instruments installed at the sites with the main or subsidiary manned stations. Calibrated poles may also be read by powerful binoculars from distances of a few hundred metres;

(b) Installing Data Collection Platforms (DCPs) operating through satellites;

(c) Periodical reconnaissance or survey with portable equipment. Calibrated poles or stakes must be installed in these areas during pre-snow period in order to assess the depth of accumulated snow. A fortnightly or monthly recce may be adequate.

4. It is also important to map the area of permanent ice cover and firn and also to monitor snowline varations periodically (say weekly or fortnightly). Monitoring of variations in snowline altitude can be made by :

(a) Actual point observation of snowline and its mapping using area-elevation relationship of the catchment;

(b) Mapping of satellite imageries on cloud free-days;

(c) Surveys by air.

6. Snow pit observation

A snow-pack consists of various layers deposited during successive spells of snowfall or drift snow. Also its different layers are subjected to varying degree of metamorphic activities. As such it is obvious that these layers will acquire different texture and physical properties except during spring when snow becomes ripe with uniform texture throughout. Thus for detailed physical investigation it is desirable to dig a pit of size about 1 m × 1 m from snow surface to the ground underneath or to a desired reference horizon and to observe various physical factors characterising snow in the wall of the pits at regular interval of depth or for each individual layer. Important factors are : density, grain size and shape, hardness, free water content and temperature. A brief description of these observations are provided below :

Density

It depends on void ratio or porosity of snow crystals and is directly measured by weighing a known volume of snow. Snow sample is collected in an aluminium cylinder of known volume (usually 1 litre) and is weighed over a pan balance. Densities of some important types of crystals/layers are as (Upadhyay 1981, Upadhyay *et al.* 1981) :

Type of crystals	*Density* (kg/m^3)
Dry flakes	30- 50
Loose dry snow	50- 90
Wind packed snow	120-300
Round or irregular grain	240-300
Cup crystals or depth hour	150-380
Wet snow	500-830
Soft ice	834
Hard ice	917

Free water content

A snowpack crystal consists of ice, air and water. The ratio of water content (%) to the total mass of snowpack is termed as free water content. For a snow pit observation, the following qualitative observations are included (Upadhyay *et al.* 1977) :

(i) Dry — When ball is not made when handful of snow is pressed in fist,

(ii) Moist — When ball is made but water does not stick to palm,

(iii) Wet — When water sticks to palm,

(iv) Very wet — When palm gets wet,

(v) Slush — When water starts dripping on pressing the snow.

Grain size

It refers to the size (length) of the majority of the crystals in the sample taken. Snow crystals are classified in the following categories :

Category	*Grain size* (mm)
Very fine	0.5
Fine	0.5-1
Medium	1-2
Coarse	4
Very coarse	>4

Hardness

It is an index of the strength of snow layer. A layer can be put in one of the following categories with reference to the hardness :

Type	*Simple hard test*
Very soft	When fist enters the layer,
Soft	When fist does not enter, but forefinger does,
Medium hard	When forefinger does not enter but a pencil does,
Very hard	When pencil does not enter but a knife does,
Ice	When knife also does not enter.

Water equivalent (w)

$w = h\rho$; where, h is depth and ρ is density of snow.

Snow kit (instruments)

It comprises all necessary instruments to carry out snowpit observations kept in metal boxes and rucksacks. Main items are :

(i) Measuring tape,

(ii) Snow sampling tubes,

(iii) Spring balance (up to

(iv) Snow cutter,

(v) Brushes for cleaning snow off the equipment,

(vi) Crystal gauge (plate comprising millimetre grids),

(vii) Magnifying glasses for observing grain size and shape,

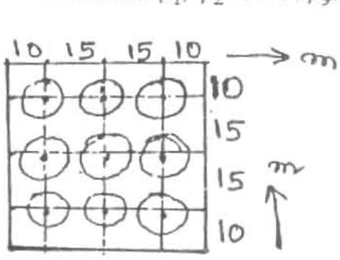
(viii) Snow thermometer with metallic cover,

(ix) Open-end aluminium cylinder (density meter),

A practical evaluation of water equivalent (w) of snowcover in observational site 50 m × 50 m .

Steps

(*i*) Form a grid as shown in figure and take snow-pit observations at each of 9 grid point (x). Suppose at these points snow depths are $h_1, h_2, \ldots\ldots .h_9$ and bulk snowpack densities $\rho_1, \rho_2 \ldots\ldots \rho_9$.



(*ii*) Form a circle of radius 5 m around each grid point and take only snowdepths observations at 10 points on the circumference of each circle. Let mean depths of standing snow along these circles be $H_1, H_2, \ldots\ldots H_9$ and standard deviation $S_1, S_2 \ldots\ldots S_9$.

(*iii*) Calculation table.

Grid pt	h	ρ	s	H	Water equivalent (w) at grid pt	w around circle
1	h_1	ρ_1	s_1	H_1	$w_1 = h_1\rho_1$	$w_1 = H_1\rho_1$
2	h_2	ρ_2	s_2	H_2	$w_2 = h_2\rho_2$	$w_2 = H_2\rho_2$
⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮
9	h_9	ρ_9	s_9	H_9	$w_9 = h_9\rho_9$	$w_9 = H_9\rho_9$

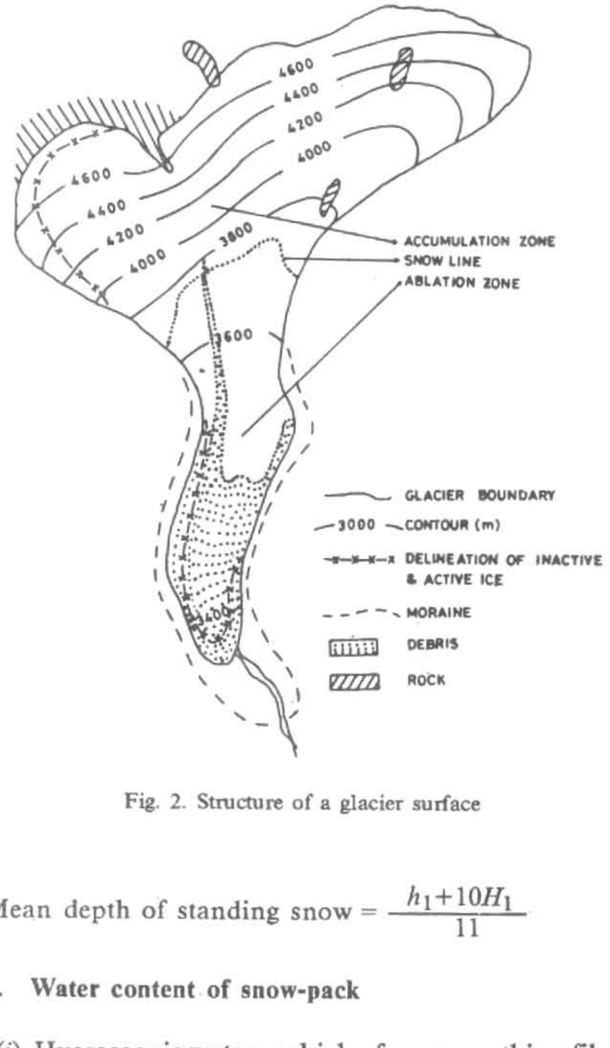


Fig. 2. Structure of a glacier surface

$$\text{Mean depth of standing snow} = \frac{h_1 + 10H_1}{11}$$

7. Water content of snow-pack

(*i*) Hygroscopic water—which forms a thin film around ice-frame work.

(*ii*) Capillary water —which is held by menisci of pores.

(*iii*) Gravity water —which perolates.

Liquid water holding capacity (w) is the maximum amount of hygroscopic and capillary water that can be held.

If H_c is cold content of snowpack, *i.e.,* the heat required to raise the temperature of pack to 0°C, then

$H_c = \rho.c_p T_s.d$; where, d is depth of snow. Heat deficient (H_d) is given as :

$H_d = \rho.d.L_{fs} + H_c$, where L_{fs} is latent heat of fusion of snow.

If H_c is expressed as the equivalent depth of water (dw) at 0°C which upon freezing within the snow would through release the latent heat of fusion raise the temperature of pack to 0°C, then

$$L_f \rho_w \, dw = \rho_{c_p} T_s d.$$

The experiments using cold calorimetry may be performed for detecting free water content of snow. This may be related to many important properties of snowcover.

8. Melting of avalanching snow

An avalanche site has 3 specific zones:

Formation zone or catchment.

Avalanche path.

Runout zone.

In formation zone fracture takes place in snowpack; it induces more fractures; gathers momentum while running down the slope and finally deposits in runout zone. This displacement of snow has following effects on melt:

Transportation to higher temperature zone.

Reduction in exposed area.

Increase in density and decrease in albedo.

If A_1 is the area of snow in formation zone with temp. T and A_2 is the area deposited in runout zone with temp. $T + \gamma Z$, γ being the lapse rate of temperature and Z the altitude difference between fracture and deposit levels then the net gain or loss in melt rate depends if the factor.

$A_2 (T + \gamma Z) - A_1 T$ is +ve or —ve.

It will give useful information if studies are taken up on these lines.

9. Mass balance studies

LAND SAT data presented on a 1 : 25000 map can be utilised to identify and measure specific glacial features like morain, degree of debris cover, crevassed area, firnline separating wet and dry snow and accumulation and ablation zone. It provides an efficient tool for mass balance study. Impositing ground trough on topographic features, contour lines can be drawn and a model glacier map as shown in Fig. 2 may be prepared. Catchment characteristics of a snow field can also be evaluated. These informations provide important inputs for mass and water balance studies.

(*i*) Water balance of a snow-bound area for a year is

$$Q_{gen} = P - L \quad (1)$$

where, Q_{gen} — Generated runoff

P — Basin precipitation,

L — Losses;

For a specified period the equation is:

$$Q_{gen} = P - (w_2 - w_1) - L \quad (2)$$

where, w_1 and w_2 are the water equivalents of snowcover at the beginning and end of the period respectively.

$L = L_i$ (interception) + Q_{sm} (change in soil moisture) + L_{et} (evapotranspiration losses)

$P = P_r$ (rain) + P_s (snow)

$P_s - (w_2 - w_1)$ may be regarded as snowmelt (M).

$$Q_{gen} = P_r + M - Q_{sm} - L_{et} \quad (3)$$

Desired basin precipitation (P) = (Areal precipitation based on available stations) $\times \dfrac{N_b}{N_a}$

where, N_b — Basin normal annual precipitation,

N_a — Normal annual precipitation based on available stations.

Interception loss can be empirically estimated from the snow-cover water equivalent (SWE) as:

$$SWE = a + bx$$

where, x is canopy density (%).

(*ii*) *Mass balance of glaciers*

From a glaciated area the met water yield is governed by 3 balance equations, *viz.*, (a) energy balance, (b) water balance, (c) ice balance. (b) & (c) combine to form mass balance. These balance equations are given by:

$\Delta w = w_p + w_l - w_r - w_f$, and

$\Delta I = I_p + I_l - I_r - I_f$

where,

w_p/I_p — Precipitation in liquid/solid phase,

w_e/I_e — Condensation or evaporation from water/ice,

w_l/I_l — Runoff of water,

I_r — Discharge of ice & snow from drift or avalanches,

I_f/w_f — Freezing of water to ice.

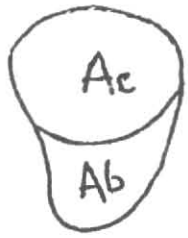
In practice mass balance can be studied by actual measurements of accumulations and ablation by installing a good network of stakes and their period, *i.e.*, monitoring as given below:

Period/year	*Accumulation (Mass)*	*Ablation (Mass)*	*Net balance (Mass)*
1	Mass = Area	× Depth	× Density

The study includes estimation of equilibrium line, the areas of accumulation and ablation zones and change in depth of snow/ice cover over the glacier field.

(iii) Parameterisation of equilibrium line altitude

Collection of mass balance data is usually a tedious exercise. It may, however, be seen that fluctuations in altitude of equilibrium line (Z_e) gives a fair idea of mass balance. Efforts should be made to relate Z_e with more common meteorological and topographic features such as air temp (T), snow precipitation (P) slope of glacier, changes in snout position (s) etc. In empirical relations $Z_e = f(T, P, \theta, s \ldots\ldots)$ the relative importance of a factor T may be ascertained by correlation coefficient r_{eT} and the nature of relationship by drawing a scatter diagram in (Z_e, T) plane.



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