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SNOW AND GLACIERS AND THEIR CONTRIBUTION TO INDIA'S WATER RESOURCES

BY

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PREFACE

Snow and ice on Himalays always attract attention of Explorers, Geographers, Philosophers and Sports persons from all over the world. One and all get thrilled with the scenic beauty and the serenity of the environment. But the scientific investigations have been very limited due to ultra high altitudes and associated communication and transportation problems. However, the scientific understanding on the subject has been developed in high latitude environment. With the availability of new technologies especially remote sensing by satellite and automatic instrumentations, it now seems possible to assess the resource potential of Himalayas.

The fact that some 60 years of average annual precipitation over the earth is locked up in ice as fresh water resource makes the phenomenon most intresting and exciting. All attempts need to be made to understand the snow and ice and its role in modifying the face of our mother planet - the earth. Through this Water Science Education Series, being brought out by National Institute of Hydrology, Dr. Jagdish Bahadur, an expert in the area who has devoted a good part of his life to understand snow and ice components has shared his information and thoughts with a larger spectrum of readers. The Institute shall feel rewarded if the contents help create awareness among the masses and educate the people about the various hydrological aspects connected with the snow and glaciers in general and Himalayan snow and ice in particular for rational utilisation of these natural resources.

This valuable document has been prepared by Dr. Jagdish Bahadur of the Deptt. of Science and Technology. Dr. Bahadur received valuable suggestions form Shri V.B. Lal, Seniour Scientist, CSIR, Dr. D.S. Upadhyaya, Direcstor (Hydrometeorology), IMD and Dr. R.K. Datta, Director, NCMRWF. The Institute is grateful to Secretary, Department of Science & Technology for providing permission to Dr. Bahadur for preparing the document.

Satish Chandra
(SATISH CHANDRA)

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1 INTRODUCTION

Nearly half of the earth's surface is subjected to snow, ice and seasonally frozen ground. About 80% of the world's fresh water resources are in the form of snow and ice. Although only 3% of this permanent snow and ice is distributed over mountains in various continents outside Polar Regions (Flint, 1971), this small amount is of great importance because of its proximity to populated areas. The existence of snow and ice is important not only as a source of water and cheap hydroelectric power but also in connection with the development of tourism and the great moderating affect on the climate. Out of all mountain glaciers, Central Asian mountains contain about 50% of the glaciers, a large proportion of which drain into the land mass of Indian Sub-Continent.

To appreciate fully the virtues of glaciers, one has to live with them. Even a casual observer can recognise its dynamic and sensitive behaviour as it constantly changes to adapt to its environment. They provide most effective and economic means of storing water, specially for arid areas bordered by high mountains. Glaciers accumulate water in winter when it is least needed and release it in summer when it is most required. Glaciers have self regulating mechanisms releasing more water in a drought year as compared to a flood year. Cold glaciers are also good record keepers preserving the history of atmospheric variations and climatic changes for hundred of thousands of years.

The present world climate is about 8°C cooler than what has been considered normal for the past six thousand million years. A further drop of only 3-4°C might be enough to get new icesheet started and once they are underway, a major climatic change would be required to stop them. The cold climate would result in sea level drop releasing a lot of land in coastal areas. The sea level drop would particularly affect arid and semi-arid regions where pluvial conditions would be established thereby changing the current deserts.

The impact of renewed glaciation would not be all negative. Many parts of the globe now barely inhabitable could become delightful places for living. The whole life including plants, men and animals have to develop interesting adaptation to the changing situation. This may appear to be an anomalous situation due to recent public debates on global warming due to greenhouse gases threatening to effect the productivity of all natural systems.

In the present text the contents include historical background of snow/ice research, snow and its characteristics, glacier and its characteristics, water resources from Himalayan snow and glacier, some pertinent observations with concluding remarks. Under each major head certain subdivisions have been made to help dissemination of information with extensive references for those who would like to do further reading on the topic of their interest. The text is followed by annexures containing glossary, names of principal Himalayan glaciers, potential hydropower of Himalayan river systems and Global Water Resources.

2 HISTORICAL BACKGROUND

Snowcover has attracted human attention because of avalanches and assessment of its water content for forecasting melt run-off and the observation of snow structure and texture. The physical investigations increased when government sponsored laboratories were established in 1936 the same year as the founding of the International Glaciological Society (Colback, 1987).

Snow research surged again during 1970s with the particpation of a new generation of scientists using more advanced theories, computer, and instrumentation. As demands continue for solutions to snow problems with new emphasis on old themes, snow research generates knowledge about snow for a variety of applications of interest to the society. A brief history of snow research is given in Table 1.

TABLE - 1 HISTORY OF SNOW RESEARCH

	Period	Names	Accomplishments
1.	Preparation (pre-1900)	-	Some early observations on snow but tools and concepts were just being developed.
2.	Discovery (1936-70)	Church, Paulcke Seligman etc.	Routine measurements Paulcke, established. Concepts from Seligman, physics provided qualitative insights. Progress on avalanches and snow-melt run-off.
3.	Recent (1936-70)	de Quervain, Dyunin, Yosida, etc.	Government-sponsored laboratories established and professional societies founded. Snow research becomes more quantitative. International comunity established. Surface energy exchange quantified. Many physical processes investigated including models of processes and properties. Widespread use of models for engineering purposes.
4.	Current (post-1970)	-	Tools become much more sophisticated. Concepts from other fields refined and applied to snow to make significant advances. Some of the "classic problems" solved but others remains. Older models and terms replaced but many problems still not completely solved.

5.	Future	Grain-scale geometry of snow quantified and this information used to develop models of physical processes and properties for a wide range of snow types. These models widely used to describe snow in engineering.

Interest in snow and glaciers of Himalayan began with the observations regarding snow line or the line of perpetual snows early in 1840s (Vohra, 1981). The Pindari glacier was first to be investigated upon (Madden, 1847) and Himalayan glaciology was accepted as a scientific pursuit by nineteenth century.

Today, basic research is closely integrated with engineering research and with technological developments in cold regions but intellectual curiosity and a romantic attraction to cold regions are still dominant characteristics of the best cold region scientists. We have to attract our scientific talent to the existing problems of the Great Himalayan glaciers.

3. SNOW AND ITS CHARACTERISTICS

In the simplest term snow can be defined as the solid form of water which grows while floating, rising or falling in the free air in the atmopshere. Snow is the aggreagate of delicate skeletal ice crystals formed in the atmopshere by sublimation of water.

3.1 Structure of Water Molecule and Ice Crystal

The water molecule consists of one oxygen atom and two hydrogen atoms. The oxygen atom shares the two electrons of the hydrogen atoms, and the two hydrogen atoms are disposed at an angle of 109° with the centre of the molecule (Fig.1a).

These molecules can join to form a crystal lattice in which each hydrogen atom lies between two oxygen atoms; this type of attachment is called a hydrogen bond. The resultant lattice is the characteristic crystal structure of ice. This structure, in which each molecule is surrounded by only four immediate neighbours, is a very open structure, and accordingly ice is a substance with an abnormally low density. The hexagonal symmetry of a snowflake is a manifestiation of internal structure of ice (Fig.1b).

Because the lattice is made up of similar layers, it is possible to slide these layers like a deck of cards without destroying the homnogeneity of the crystal lattice. This process, which describes how ice crystals deform under stress, is called intracrystalline gliding (Meier, 1964).

When ice melts, the lattice structure is partially destroyed and the water molecules are packed more closely together, causing water to have a higher density than ice.

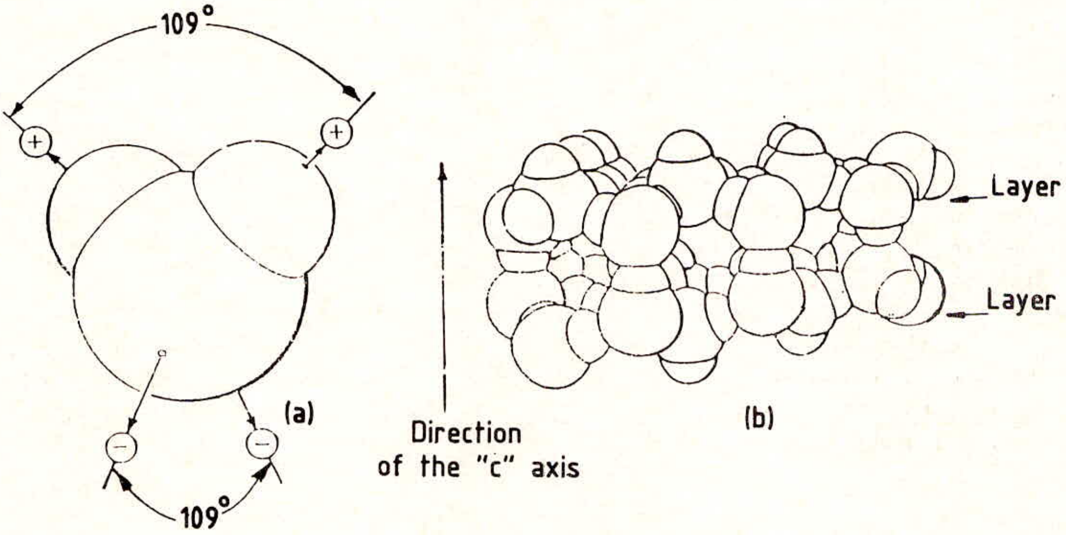


Fig. 1. Structure of a) water molecule; b) ice crystal

However, many of the hydrogen bonds remain, and aggregates of molecules with the open-lattice structure persist in water at the freezing point. With an increase in temperature, some of the aggregates break up, causing a further increase in density of the liquid. At a temperature of 39° F, the normal expansion due to increase in molecular agitation overcomes this effect, and at higher temperatures water shows the normal decrease in density with rising temperature.

The ratio of water content to the total mass of snow pack is termed as free water content. For a snow pit observation, the folowing qualitative observations are included:

i) Dry - When ball is not made when handful of snow in 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 by pressing the snow.

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

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

Hardness 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.

3.2 Usual forms of snow crystals

In fact, snow is very beautiful and intriguing object in the nature and more than 6,000 different forms of the crystal have been mapped and it is felt that the listing is still incomplete. The growth of snow crystal is a subject of great interest to all, particularly to Physicists (mason, 1961). Common forms of snow crystals associated with various temperature ranges is given below (Mason, 1971). Usual forms of snow crystals at the time of snowfall (Garstaka, 1964) are shown in Table 2 & Fig. 2

TABLE - 2 USUAL FORMS OF SNOW CRYSTALS

Temperature Range	Crystal Types
-3 to 8°C	Needles.
-8 to 25°C	Plates, Sector stars.
-10 to -20°C	Stellar dendrites.
-20°C	Prisms, Single Crystals, Twins.
-30°C	Clusters of hollow prisms

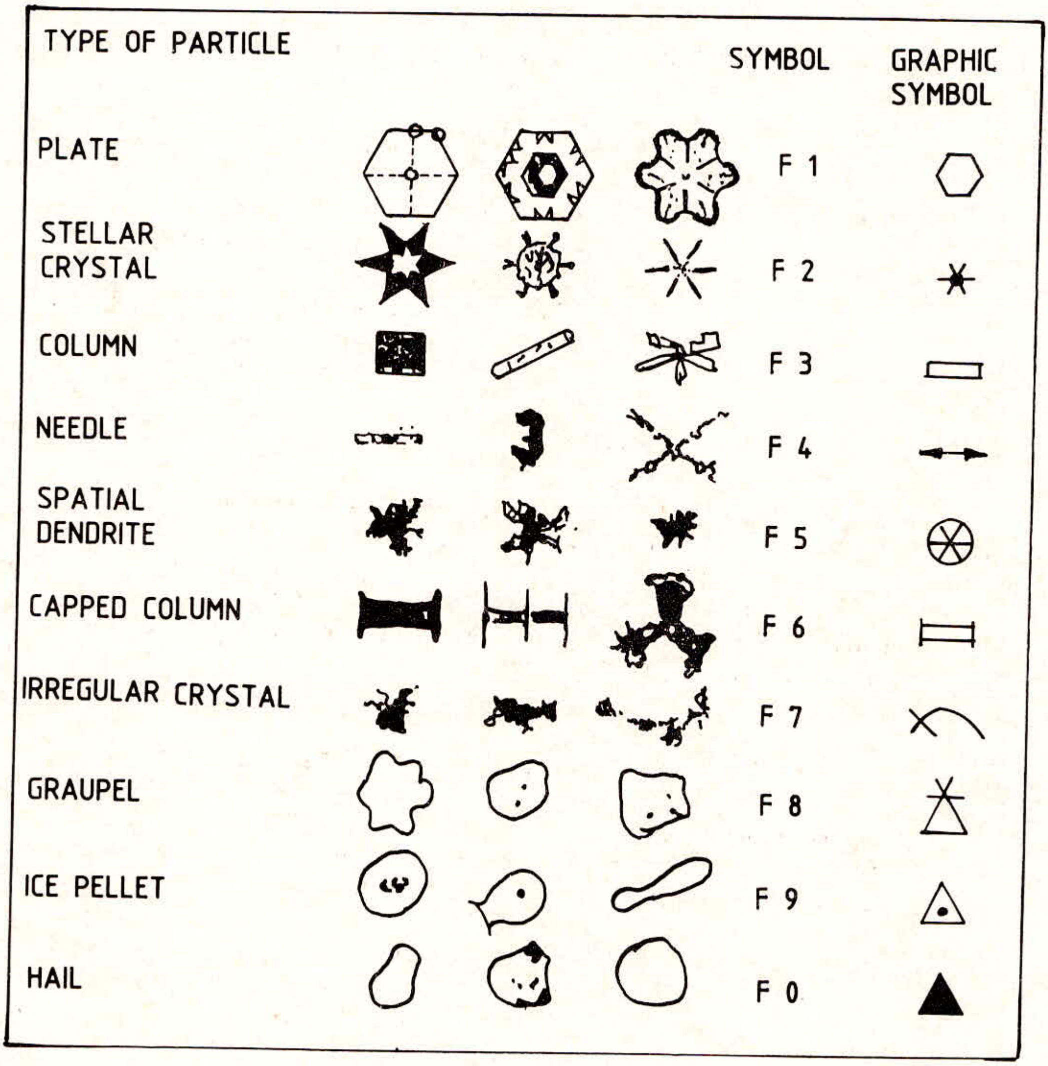


Fig. 2. Classification of usual forms of snow crystal

3.3 Density range of snow forms

The density of variuos types of snow crystals is given in Table 3 (Paterson, 1969).

TABLE -3 DENSITY RANGE OF SNOW FORMS

Types of Crystals	Density (gm/cm^3)
"Wild snow" (new snow at low temperature in calm)	0.01 - 0.03
New snow (immediately after falling in calm)	0.05 - 0.07
Damp new snow	0.1 - 0.2
Settled snow	0.2 - 0.3
Depth hoar	0.2 - 0.3
Wind packed snow	0.35 - 0.4
Firn	0.4 - 0.85
Very wet snow and firn	0.7 - 0.8
Glacier ice	0.85 - 0.91

4. GLACIER AND ITS CHARACTERISTICS

In the simplest term a glacier can be defined as a body of natural landborne ice that flows. In a natural setting, a glacier is a mass of compacted ice originating in a snow field (Fig. 3 & 4). They occur in those parts of the earth where the rate of precipitation is greater than the rate of melting of the snow. The ideal locations are the polar regions and the higher mountain ranges. In general, glaciers are complex, dynamic systems senstive to their surroundings and constantly change their shape and form to adapt to its environment.

Glaciers exist in a wide variety of forms and characteristics. They range in size from continental ice sheets to tiny masses (a few hectares in extent) and in shape from steep narrow ice gaskets in high mountains to smooth sheets lying on flat plains (Fig.4). Some are active ice streams in areas of very high precipitation and large amounts of meit water run-off, whereas others occur in such cold environment that yearly nourishment is only a few millimeters and run-off is negligible.

4.1 Glacier classification

Wide differences in glacier appearance, regime, and hydrological characteristics could be described by a classification based on shapes, temperature and activity (Meier, 1964) as detailed below:

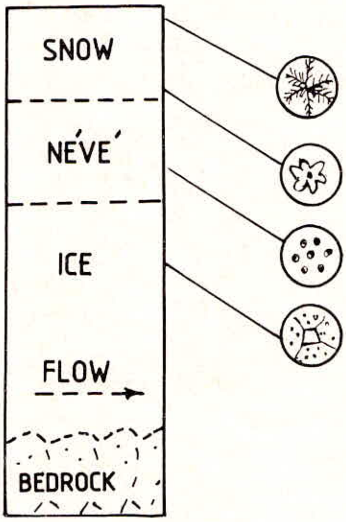


Fig. 3. Formation of a glacier ice from snow.

4.1.1 Morophological classification

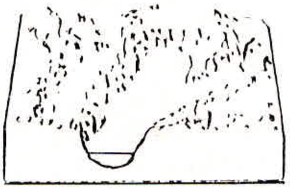
This is characterised by distinctive hypsometric (area - altitude) graph and include continental glaciers - extending in continuous sheets and ice moving in all directions. Other form of glaciers which are confined to a more or less marked path, directing its main movement include valley glaciers, cirque glaciers, etc. Another form of glacier which is spread inlarge or small cake like sheets over a level ground or at the foot of glaciated region such as piedmont glaciers.

4.1.2 Geophysical classification

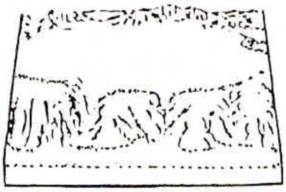
This is based on thermal characteristics of glacier ice and could be broadly classified.

a) Temperature Glaciers

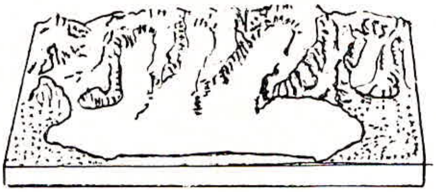
The temperature corresponds to the melting of ice throughout the body of these glaciers. With the exception of winter time when the top layers may be at lower temperature these glaciers produce copious run-off.



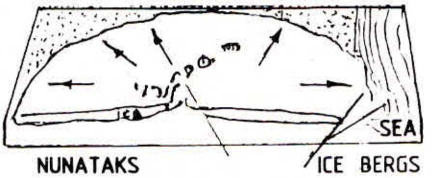
a) VALLEY GLACIER



b) ICE CAP



c) PIEDMONT GLACIER



d) CONTINENTAL GLACIER

Fig. 4. Different kinds of glaciers

b) High- Polar Glaciers

The temperature is below the freezing point to a considerable depth in these glaciers and even in summer the temperature is so low that as a rule there is no melting.

c) Sub-Polar Glaciers

In these glaciers the summer temperature allow surface melting and a formation of liquid water but the main mass of ice at depth is below the freezing temperature so that the liquid water re-freezes at lower horizons. There can be little run-off from this type of glaciers except in margins.

4.1.3 Dynamic classification

The activity or passivity of glacier depends on its depth, speed of flow and material balance (Fig.5). The rate of movement of active glacier is generally very high because it must transport a large amount of precipitation from one area to another, where the amount of melting is likewise high. In general, active glaciers occur in maritime environments at relatively low latitudes and passive glaicers occur in high latitudes and in very continental environment. The activity of a glacier has no relation to whether its snout is advancing or retreating at any instant.

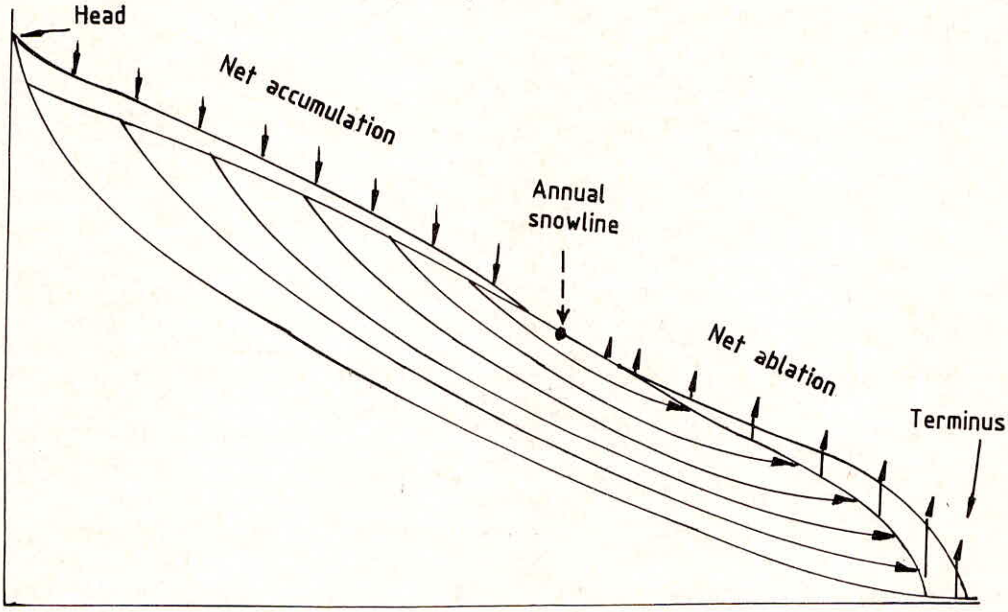


Fig. 5. Long Section of ideal Valley glacier showing area of accumulation and area of ablation.

4.2 Glacier Movement

Most of the glaciers move slowly (velocity about a few cms per day). In Fig.6 transverse velocity profile AA′ A″ as viewed from above demonstrates that the icestream flow more rapidly at the centre as compared to its margin. A verticle pipe AB imbedded for surface to bed will assume the shape A′B′ (Fig.7) thereby demonstrating that the total surface movement is the sum of internal flow and slip upon the bedrock. The velocity measurement on the glacier surface represents a summation of what is happening by solid flow within the glacier and by slippage over its bed. Even if slip started by unevenness of the bed, it contributes the larger fraction of the total movement of most glaciers. In general, warm glaciers move more rapidly and experience greater velocity and variation as compared to cold glaciers.

An ice stream flowing in an uniform channel has its greatest thickness, highest velocity and largest discharge at the firm line. Ice flow is laminar and is directed downward from the surface in the accumulation area and upward in the ablation area. The glacier ice at the snout comes from the heads of the glacier and not from the intermediate positions. When the glaciers velocity increases, extending flow occurs and a glaicer advances and thins and when the velocity decreases, compressive flow occurs and a glacier shrinks or thicknens (Fig. 8). An Ice fall is a reach of extreme extending flow and the plunge pool at its base is a realm of extreme compressing flow.

Glaciers exhibit unusual velocity variations. One common phenomenon is the movement of a wave of increased discharge through a glacier at a speed several times normal. This behaviour has been described and analysed as a kinematic wave. Such waves enable a glacier to adjust to increase in material budget in a much shorter time than that required to transport the additional material to the wastage area. Glacier surges involve a large and rapid increase in basal slip. Field observations suggest that this is due to accumulation of water in cavities beneath the glacier, which increases the hydraulic pressure to the point that the contact between the glacier and its bed is reduced. The relationship between kinematic waves and surges are not yet fully understood (Sharp, 1988).

4.3 Glacier Erosion

It takes place by abrasion and by plucking, or bodily removing rock fragments (Fig.9). It is stronger in warm glacies as compared to cold glacies. The effectiveness of abrasion compared to plucking is a subject of controversy but in jointed rocks plucking is probably superior. Glacier erosion can be profound. Ice streams have widened and deepened end mountain valleys by hundreds of metres and continental ice sheets have excavated closed rock basins by hundreds of metres below sea level.

Direct evidence of glacier erosion on exposure of bed rock is expressed mostly in the form of striae, grooves, smoothing, rounding and sharp truncation of internal

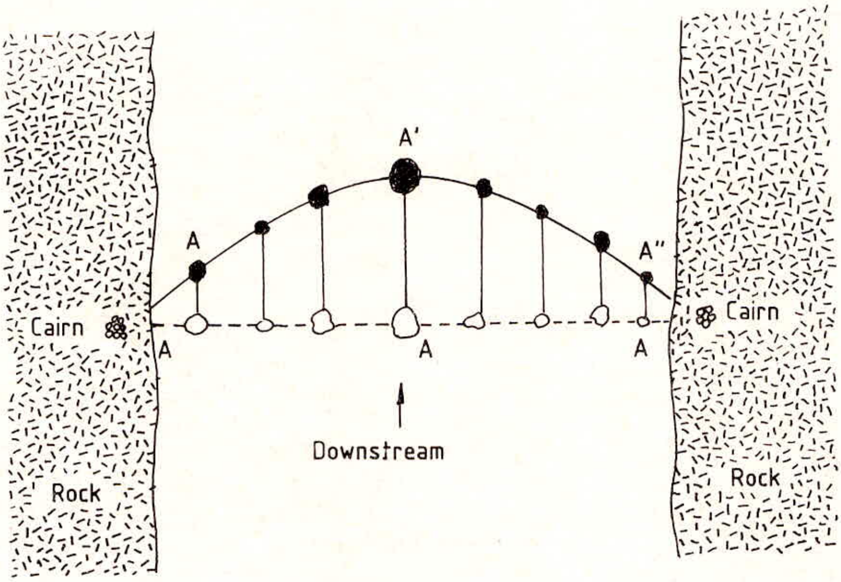


Fig. 6. Transverse velocity profile AA′ A″ as viewed from above showing that the icestreams flow more rapidly at the centre as compared to margins.

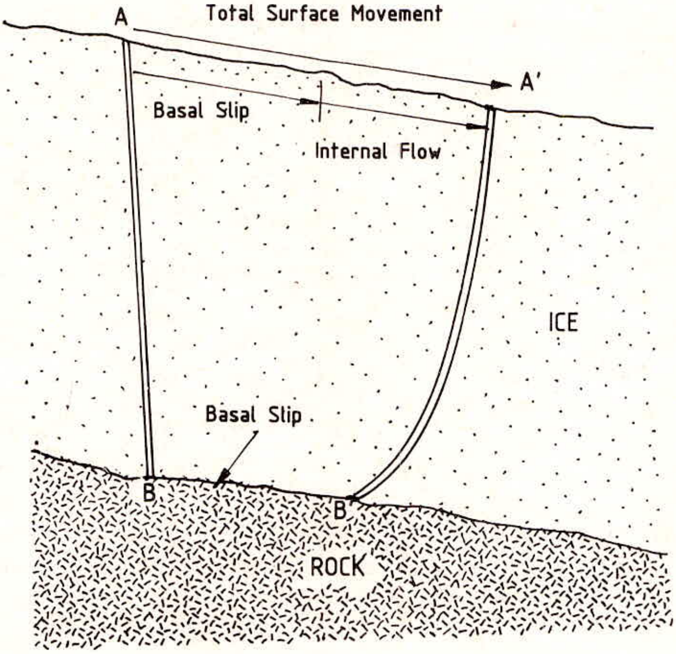


Fig. 7. Vertical Section cut parallel to flow direction.

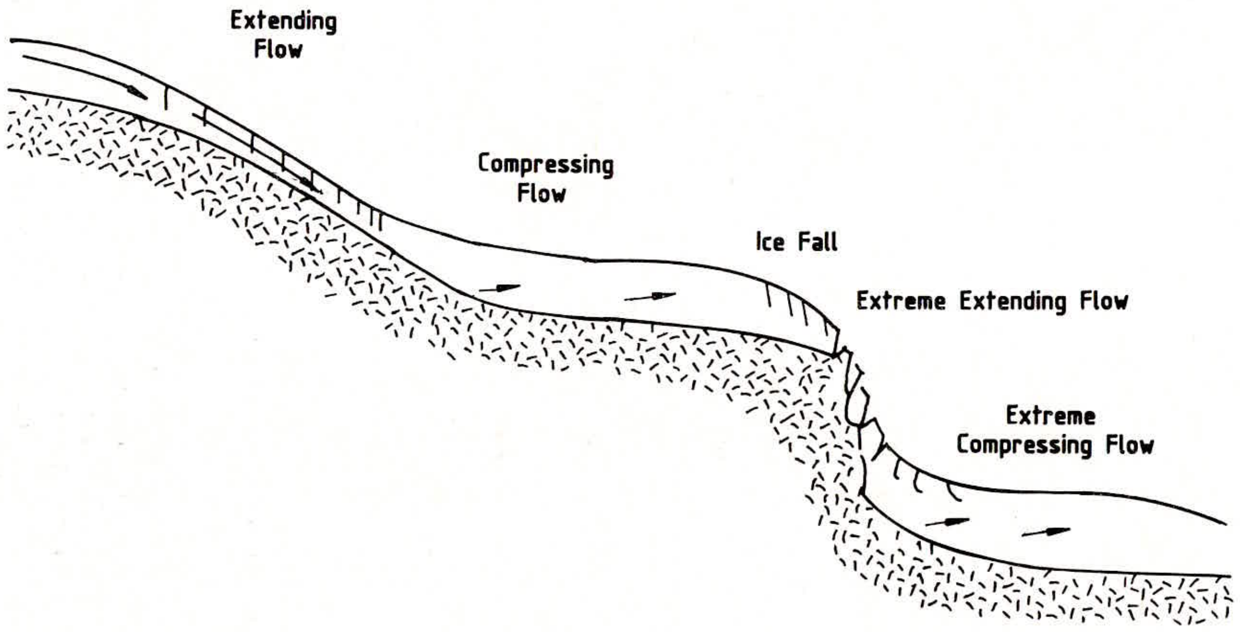


Fig. 8. Extending (thinning) and compressive (thickening) glacier flow.

rock structure. Larger features such as U-shape and hanging valleys, glacial steps, whalebacks, rock drumlins, roches moutonnees, excavated lake basins, cirques and horns contribute to the scenic appeal of glaciated mountainous landscapes. Abrasion has created most of the smaller feature, and plucking has usually dominated in the forming of larger landscape features. Undercutting of steep slopes by glacier sapping, larger through plucking, plays a major role in the formation of cirques and other forms along high crestal divides. Some surface markings and erosional land-forms indicate the direction of ice movement.

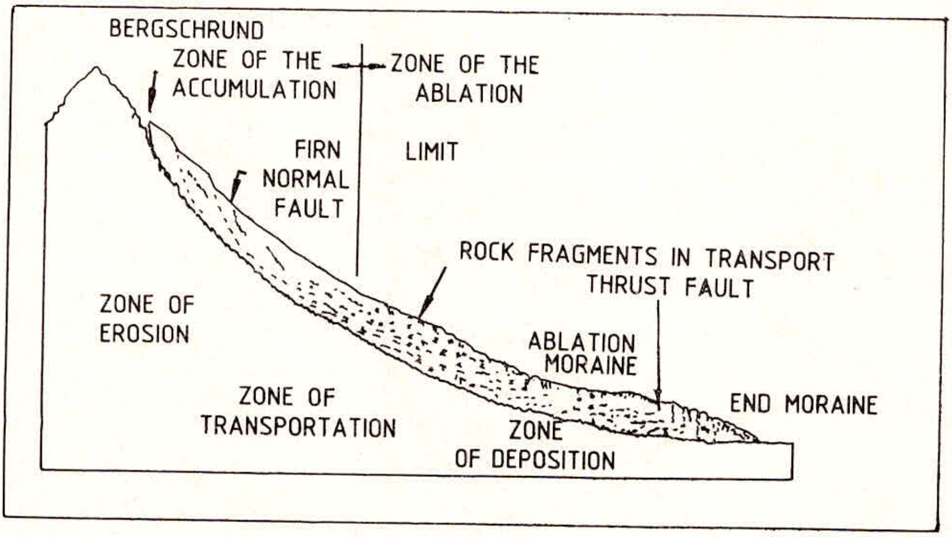


Fig. 9. Glacier abrasion and erosion due to ice flow.

4.4 Glacier Transport and Deposition

Glaciers have almost unlimited capacity to transport rock debris. No particle is too small, no block too big and nearly all are carried in suspension, within or upon the ice. A principal drawback to glacier transport is slow pace averaging something less than one metre per day. Associated agents of transport taking over the glacier's margin such as debris' flowage, running water, and wind, operate at much faster pace. Everything glacier transport must ultimately be laid-down. Some depositions occurs beneath the ice but much transported debris is either dumped along the glacier edge or carried away by associated processes. Wind and water carry the final debris, sand, silt and dust, far beyond the glacier.

Glacial deposition consists of rock debris transported, often over considerable distances, by ice before being deposited directly as till or given to the streams of melt water for further transport and deposition as glacio-fluvial material.

Depositional features most commonly seen include moraines, erratics outwash plains and trains, ground-moraine sheets, drumlins and various ice - content features such as kettle holes, kames and eskers. Glacioeolian deposits, derived by wind from outwash plains and river flood plains make up sand dune sheets and mantles of loess (dust). Moraine-dammed lakes enhance the scenery.

Glacial-lake deposits containing sedimentary couplets of clay and sandy silts (varves) are valued for measuring geological time.

4.5 Glacier Mass Balance

The main part of the change in mass is usually assumed to take place in a relatively thin surface layer of the glacier. This is the only part normally involved in heat balance measurements. In addition to surface accumulation and ablation measurements made by snow-profiling and stake elevation determinations, subsurface accumulation (by refreezing of meltwater) and ablation (percolation of meltwater) must be included for a correct assessment of glacier mass.

Two types of measurement systems can be used:

i) the stratigraphic system;
ii) the fixed date system.

The stratigraphic system is based on the existence of an observable summer surface which is assumed to be formed at the time of minimum mass at the site. The summer surface may be an identifiable horizon of concentrated debris particles, a discontinuity between old ice or firn below and much younger snow above. While the fixed date system involves measurements made at certain specified days or whenever possible, and the measurements are not related to any observable features in the snow, firn or ice.

Glacier mass balance is the most meaningful description of its hydrological cycle and a way to evaluate the water storage aspects and associated processes of snout movement, variation in glacier thickness, erosive & deposition capacity resulting in creating the glacial landscape (Fig.10).

Mass balance in the life history of glacier at any particular time stage is either positive or negative displaying a surplus or deficit of ice on the glacier body. Surplus mass balance results in glacier advance while deficit results in glacier retreat. The glacier advance or retreat create erosional and depositional features modifying the geomorphological landscape.

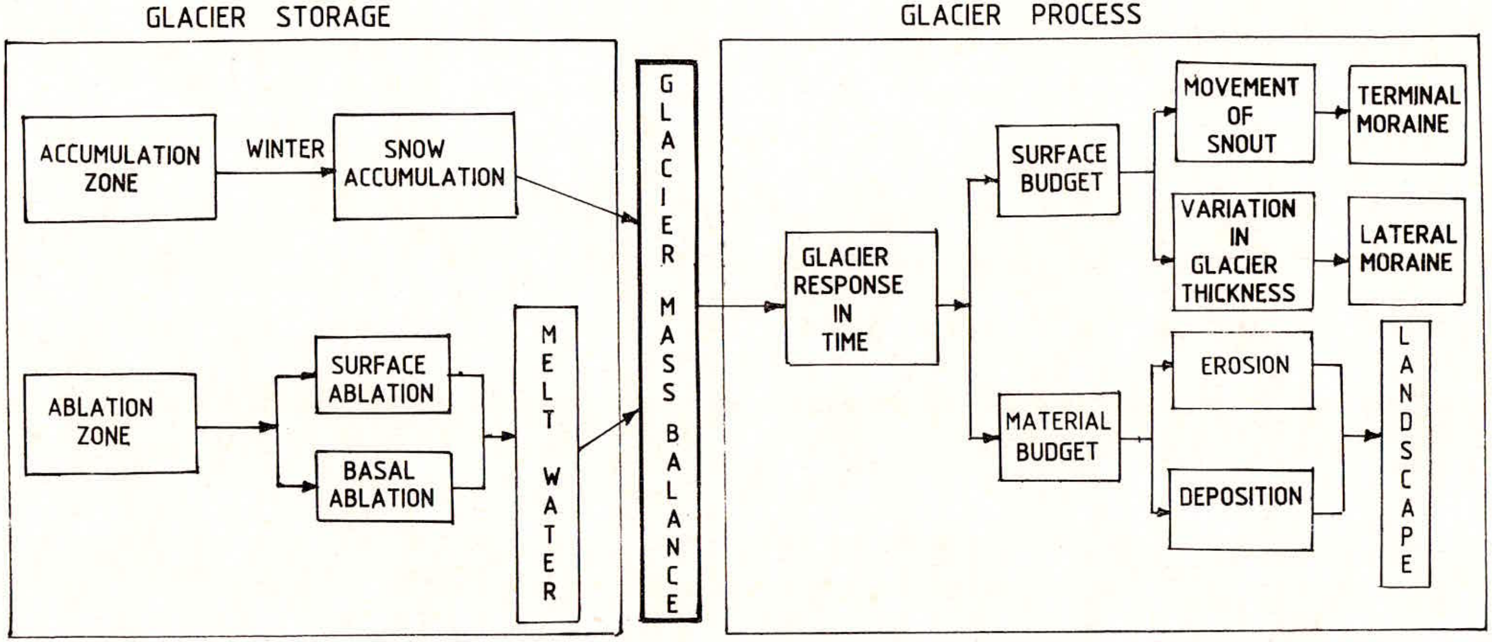


FIG. 10

Fig. 10. Simplified system of glacier storage, mass balance and associated processes.

The mass balance is mainly related to temperature and precipitation but other micrometeorological elements e.g. radiation, humidity, evaporation and wind direction play their role in altering the balance.

Mass balance studies on Himalayan glaciers are limited (Raina et al, 1977; Kaul, 1990) and extensive work is needed for 5 to 10 years on some selected representative glaciers to know their meltwater contributions to our river systems.

5. SNOWMELT CALCULATIONS AND FORECASTING

There are two main approaches to calculating snowmelt, the so-called energy budget or balance approach and the temperature, degree day method (Quick & Pipes, 1988). It is essential to understand the physical basis for snowmelt before a proper judgement can be made between the various methods. If the full energy budget approach is to be used, it must be asked whether enough information can be obtained to apply the full physical equations, and whether it is economically feasible to obtain such data coverage for large regions. On the other hand, if the energy exchange processes are reasonable represented by air temperature variations, then the degree day approach is a very attractive alternative.

A problem with the degree-day approach is that the melt factor can vary with season and with elevation. Comparison of degree-day results with an energy approach reveals that the constant degree-day melt factor results from the seasonal increase of shortwave radiation as the season progresses and also from the decrease of albedo as the snow surface matures. In reality, the melt rate will not go on increasing linearly with temperature, but will tend to reach an asymptotic limit which is set by the available incident radiation. At higher elevations, shortwave radiation is even greater, but air temperatures are lower, so that melt rate factors for the degree day approach need to be increased to model the melt which occurs at such elevations.

The energy exchange at the surface of a snowpack is made up of four major components.

1. The shortwave radiation exchange, consisting of incoming solar radiation, and the reflected outgoing shortwave radiation. This shortwave component depends on the time of year, the site exposure, cloud cover, and snow albedo.

2. The longwave radiation exchange depends on black body radiation from the snow itself and from clouds and tree cover, and grey body radiation from the overlaying air mass. Under clear skies, the net longwave is outgoing, or negative, unless air temperature exceeds about 20°C. Under cloudy conditions and also under tree cover net longwave can be positive at temperatures above freezing.

3. Convecting heat transfer is produced by turbulent heat exchange between the air mass immediately above the pack. This heat transfer is dependent on both wind and air temperature and particularly on the stability of the

air mass above the snowpack. A warm air mass above the cold snow surface tends to be stable, resisting any downward transport of heat to the snowpack, unless there is enough wind to produce turbulent mixing. This turbulent heat transfer is governed by the Richardson number, R_I, which is a measure of stability. The bulk Richardson number, defined below, is essentially the air temperature divided by the wind speed squared. As air temperature increases, and if the wind is only moderate, the stability can increase to the point where very little convective heat transfer can occur. Convective heat transfer is therefore self limiting and becomes quite small at higher air temperatures, unless there is very strong wind.

4. Advective heat transfer, often termed condensation melt, is caused by the transport of moisture to and from the snowpack. Whether condensation occurs, releasing latent heat to the snow, or whether evaporation occurs, cooling the pack, depends on the relative vapour pressures of the air and the snow surface. Wind is once again an important factor and so is stability, as was discussed for convective transport. Advective heat transport can therefore produce snowmelt if the dewpoint temperature is above freezing, but, like the convective heat transport, becomes limited at higher temperatures by the stability of the warm air mass.

A simple set of equations has been developed which expresses the various snowmelt components in terms of millimeters of snowmelt per day, either negative or possitive. Various simplifying assumptions have been used to write these equations, but they are useful to illustrate the relative importance of the various melt components.

5.1 Simplified Energy Components

5.1.1 Shortwave - energy input

$$\text{Melt} = I_S (1 - C_L) (1 - A_L) \text{ mm.} \quad - \quad (1)$$

where C_L is cloud cover, A_L is the albedo of the snowpack and I_S is the incident solar radiation, which varies seasonally and with latitude and with atmopsheric conditions. At 50° North, I_S can be expressed in terms of milimeters of melt equivalent per day instead of Langleys per day,

$$I_S = 55 - 38 \text{ COS } 2\pi \text{ n}/365 \text{ MM/DAY} \qquad (2)$$

The albedo and cloud cover reduce the potential melt values of equation (2) to the net values expressed by equation (1).

5.1.2 Longwave Radiation

Stefan's law can be expanded in terms of the temperature above freezing, T, so that the longwave black body radiant energy, I_L , can be expressed as a linear function of temperature plus small higher order term,

$$
\begin{aligned}
I_L &= \sigma\,(273 + T)^4 \text{ Longleys} \\
&= \sigma\,.273^4 \;\; (1 + 4T/273 + 6T^2/273^2 + \ldots.. \\
&= 661\ (1 + 0.015T + 0.0001T^2 + \ldots.)\text{ Langleys/day} \\
&= 82.6\ (1 + 0.015T + \ldots..)\text{ mm/day} \qquad (3)
\end{aligned}
$$

Under clear sky conditions in an open, tree free, area, the net longwave radiation received by the melting snowpack is the difference between the black body radiation of the O°C snowpack and the incoming grey body radiation from the clear sky. Various estimated values for the grey body radiation are available (U.S. Corps Snowmelt Report, 1955). All of the equations show a small dependence on humidity of the atmopshere, such as equations due to Brunt and Angstrom. The simplest equation, from the Lake Hefner study, is

$$I_{LA} = \sigma T^4 \;\; (0.749 + 0.0049\ e_a\ ) \qquad (4)$$

where I_{LA} is the atmospheric longwave radiation, and e_a is the vapour pressure in millibars. The dependence on vapour pressure is so small that it is reasonable to accept the values,

$$I_{LA} = 0.757\ \sigma\ T_4 \qquad (5)$$

The net clear sky incoming longwave radiation, I_{LN} , can therefore be written, using the linearization of equation (3).

$$I_{LN} = 661\ [(0.757\ (1+ 0.015T_A\ ) - (1+ 0.015T_S\ )] \text{ Langleys/day} \qquad (6)$$

where T_A is mean air temperature and T_S is the snow surface temperature, which is zero for a melting snowpack.

$$I_{LN} = 7.51\ T_A\ - 161 - 9.92\ T_S \text{ Langleys/day} \qquad (7)$$

In snowmelt equivalent,

$$I_{LN} = 0.94\ T_A\ - 20.1 - 1.24\ T_S \text{ mm/day} \qquad (8)$$

For a melting snowpack, T_S is zero, and I_{LN} does not become positive until T_A exceeds 21.4° C.

5.1.3 Net Longwave under cloudy conditions

Clouds, temperature, T_C , act as black bodies, so that under 100% cloud cover, the net incoming longwave, I_{LNC}, is

$$I_{LNC} = 9.92\ (T_C - T_S)\ \text{Langleys/day} \qquad - \qquad (9)$$
$$= 1.24\ (T_C - T_S)\ \text{mm/day)}$$

The clear and cloudy sky equations can be combined into an expression for the net longwave exchange, I_{LNT}, for a partial cloud cover fraction, C, so that, for a melting snowpack at O°C,

$$I_{LNT} = (-20+0.94\ T_A)\ (1-C) + 1.24\ T_C \times C\ \text{mm/day} \qquad - \qquad (10)$$

The cloud temperature can often be approximated by the dew point temperature, which is approximately the minimum air temperature.

5.2 Convective and Advective Heat Transfer

The U.S. Corps of Engineers (1955) and NOAA (Anderson, 1976) present equations for convecting and advective heat transfer. Anderson refers to the question of air mass stability, but does not incorporate the results into a final relationship. The following equations are an approximate estimation of the net heat transfers which have been developed from the earlier work.

Under neutrally stable conditions the convective heat transfer, Q_C, is approximately,

$$Q_C = 0.113\ (p/101)\ T_A \times V\ \text{mm/day} \qquad - \qquad (11)$$

in which p is the atmopsheric pressure in kN/m² for the elevation being considered, T_A is the mean temperature and V is the wind speed in kilometers per hour.

Similarly, the advective, or condensation, melt Q_A under neutrally stable conditions is approximately,

$$Q_A = 0.44\ T_d \times V\ \text{mm/day} \qquad - \qquad (12)$$

where T_d is the dew point temperature, which can be approximated by the minimum air temperature.

Both the convective and advective melt rates are reduced by a factor R_M which is a function of the bulk Richardson number R_I. A linearization of R_M, subject to the limitations give below, is

$$R_M = 1 - 7.7\ R_I \qquad - \qquad (13)$$

$$R_I = \frac{2_g . Z_A \, T_A}{(T_A + 273)\, U^2_A} = 0.095 \frac{T_A}{U^2_A} \qquad - \qquad (14)$$

where V is the wind speed at a reference height Z.

This linearization is reasonable for R_I between +0.12 and -0.1. For positive air temperatures, the R_M factor is not less than zero, and for negative temperatures, R_M increases to about 1.8 and then slowly goes a little higher.

This R_M factor is based on idealized laboratory conditions. In steep mountain terrain, our own studies of snowmelt indicate that stability is greatly reduced by 'terrain mixing" caused by large scale roughness and slope. Consequently R_M may increase by as much as a factor of 2.5 times, which is an additional "terrain mixing" factor.

There are advantages to be gained from using energy equations for calculating snowmelt. The physical basis of the equation makes it possible to estimate snowmelt for forested and open conditions, for clear or cloudy weather, for various slope and aspects of mountainous watersheds and for changes in elevations. It is also possible to argue the impacts of changing forest cover or the snowmelt that would be exprienced under extreme and unusual weather sequences. Some simplified energy relationships will be tested against measures point snowmelt data for both open area melt and forested melt.

In this study, data on radiation, cloud cover, etc., have not been available, except for data from the U.S. Army Corps laboratories (1952). The factors which must be described are the cloud cover, albedo, wind cloud temperature and dew point temperature. All other factors can be estimated from known physical behaviour. As reasonable approximations, it has been found possible to represent these various factors with temperature-based estimates. For example, the cloud cover has been assumed to be related to the daily temperature range,

$$(1 - C_L) = (T_{MAX} - T_{MIN}) / D_R \qquad - \qquad (15)$$

in which C_L is the cloud cover fraction, T_{MAX} , T_{MIN} are the daily maximum and minimum temperatures, and D_R is the daily temperature range for open sky conditions at a certain elevation in the watershed.

The wind tends to produce a decrease in daily temperature range, so that cloudy conditions are also windy conditions.

$$V_b = K_R \, (T_{MAX} -_{MIN})^{-1/2} -Kv \qquad - \qquad (16)$$

in which K_R and K_V vary slightly with elevation.

5.3 Application to Snowmelt Forecasting

Operational forecasts are usually required for longer periods than one day. Short term forecasts might typically be for the next 10 days, then medium range forecasts of a month and also seasonal inflow forecasts. This is done by using the latest snowpack information, flow and weather data to define the present status of the watershed. Then the future weather conditions for the forecast period, which might be the whole season, are specified by selecting a previous year of observed weather. This process gives a possible pattern of snowmelt runoff, and the model automatically calculates the residual snowpack potential. The whole process is repeated using a range of historical weather sequences from the data record, and the resulting forecasts represent the probable range of flows which could occur throughout the forecast period. This procedure can be updated with the latest snopack, flow and weather informaion as the season progresses, so that better, updated forecast estimates can be made. This procedure does not give a unique answer, but it also identifies a statistical range and a most probable outcome. Melt-volume forecasts prepared in this manner are particularly good, because, even if short term errors occur, these errors tend to be self compensating later on. This compensation occurs because, if too much flow is generated earlier, then the model estimates as lower residual snowpack, so that later flow estimates will be slightly under-estimated. Forecasts of this type have been utilized by British Columbia Hydro and Power Authority for some years, and are used as inputs to a dynamic programming package for optimization of power production.

For operational purposes there is also considerable value in monthly forecasts. Typically these monthly forecasts are reliable to within ± 7% to 9%. Shorter term forecasts of snowmelt, for the next few days, can be accurate to within +10% but at this time scale the main interest is likely to be the short term response to rain. This rain response is highly dependent on data coverage. Quantitative precipitation forecasts are still quite inaccurate, so that a forecast depends primarily on measured data and the delay time in the system before rainfall runoff reaches the reservoir. Accuracy for such events is quite variable and reliability might only by ±15 to 20%. These error estimates are illustrative of the operational performance that can be expected for regions where snowmelt is the dominant factor, but where rain is still of some significance.

5.4 A Summary of the Snowmelt Issues

Much snowmelt research has attempted to measure and calculate snowmelt at a point in a watershed. The U.S. Corps Lysimeter studies are a prime example. However, when forecasting runoff, snowmelt is required for the total watershed, which will vary is elevation, aspect, and the existence or lack of tree cover. A major issue is therefore the watershed wide distribution of meteorological data which will depend on temperature lapse rates and precipitation gradients,both by area and by elevation.

There is a strong contrast between the snowmelt estimation problems in the mountains. The mountains appear to be highly complex and therefore very difficult. In reality, the mountains exhibit a strong orographic discipline, so that precipitation and tempeature gradients can be defined. Snowcover is also a function of elevation and snowpacks are deep, so that soil freezing is not a problem as it happens in plains. The mountain watershed is steep and has a fast runoff response and the protracted melt season makes loss estimation more feasible.

Small mountain watersheds, especially in the coastal regions, are also susceptivle to rain on snow flooding. From the snowmelt equations, it is seen that rain does not produce much additional snowmelt. Rain or snow floods are nevertheless severe for several reasons. In low snow areas, the snow can supply melt water which refreezes in the soil, producing the conditions for high runoff. In the mountains, and higher snowpack regions, the snowmelt satisfies many of the losses and soil moisture storages, so that the effective rainfall runoff is greater. Slow flow studies through homogeneous snowpacks, (Colbak, 1979) show that rain rapidly ripens and modifies a snowpack, developing pathways by which runoff can rapidly move to the river system. Under heavy rain conditions there is therefore little delay of runoff by the snowpack, and most of the rainfall, together with additional snowmelt and capillary water retained in the pack, can be released to the stream system. These are the conditions which can lead to severe flooding in plains or the mountains.

5.5 The Advantages of Snowmelt Modelling

The snowmelt runoff problem is complex, involving the interaction of many aspects of the watershed system. To analyze such complexity, it is necessary to represent the various aspects of behaviour in a watershed computer model. There are many advantages to such a system; for example, a model can combine different types of data into a coherent structure. Inter-relating the data in this way makes it possible to check on the consistency of data from different sources and reveals which is the most valuable data for forecasting purposes. By contrast, statistical analysis of data is much more limited, requiring long data records, and it is difficult to incorporate new information or to deal with the time distribution of runoff. The watershed model is therefore a valuable research tool; it is also a data handling system and, finally, by representing the physical system, it can be used to make forecasts of the snowmelt runoff.

The basic snowmelt processes are well understood but there are various practical and theoretical difficulties in determining the values of the various energy components, which from a fundamental point of view, are all derived from incoming solar radiation.

Net shortwave radiation is greatly influenced by the changing albedo of the snowpack and by atmospheric conditions, especially cloud cover, which are difficult to quantify.

Net longwave radiation plays opposite roles under open sky conditions and under cloudy or tree covered conditions. Under open sky conditions with no tree cover, net longwave represents a substantial loss of energy unless air temperature is quite high. Under cloudy or treed conditions net longwave can be the principal source of melting.

Convective and advective energy transfers are generally smaller components of total melt, because these heat transfer processes are limited by the inherent stability of a warm air mass over a cold snowpack. These components become increasingly limited as air temperature increases, unless there is considerable wind to induce turbulent mixing. However, terrain roughness acts to decrease stability and tends to increase these melt rates.

It is shown that open area melt is dominated by net shortwave radiation, although net longwave can be the major factor during cloudy conditions. Forested melt is dominated by net longwave and so is well described by air temperature data. A simplified set of energy budget equations is presented above which can by controlled by air temperature alone. Shortwave radiation is specified as a function of season, slope and aspect. Cloud cover and wind are estimated from temperature range and albedo from cumulative melt. Consequently, a comparison of energy equations and degree day melt relationships show that in forested conditions the degree day approach is adequate. In open areas, where shortwave radiation is important, an energy budget method is better.

Rain on snow is widely recognized as a major source of flooding, especially in urban and smaller mountain watershed situations. Although the rain induced melt is small, the antecedent snowmelt can precondition the watershed, so that the rain can produce considerable runoff, especially if the ground is impervious or frozen.

6. WATER RESOURCES FROM HIMALAYAN SNOW & GLACIERS

Snow and Ice has vast potential for water resource development in India (Bahadur, 1972). This is particularly valid for Himalayan snow and glaciers where the present status of information from research and field investigations is still in its infancy. With the increasing exploitation of water for irrigation & power, there will be an increasing demand for more detailed scientific information for snow cover and glacier drainage for an optimal utilisation of water resources and the management of the environment including innovative regeneration strategies for this unique high altitude environment (Bahadur, 1973, 1976, 1978, 1981, 1982, 1983, 1987, 1988, 1989).

6.1 Uniqueness of Himalayas

'Himalaya' means the store house of snow and ice and is more commonly referred as the abode of eternal snow. According to Bhagvad Gita, the concept of bulk, immobility and steadfastness on our earth reached its limit and exhausted in one word - the Himalaya. The Himalayas are the world's mightiest mountain. No other chain has any mountains higher than 7,000m (asl). The Himalayan range has 14 mountain peaks over 8,000m and hundreds over 7,000m (asl). The Himalayan range extends through 7 countries the USSR, the People's Republic of China, India, Bhutan, Nepal, Pakistan and Afghanistan and is also called the 'roof of the world'. The Himalayas still preserve many spots unspoiled and unpolluted by man, making the area perhaps the greatest storehouse of secrets in the world. Range upon range of magnificant mountains, snow clad, their peaks wrapped in mystery and sublime beauty, the Himalaya will never lose their fascination for mankind. One has to raise oneself over terrestrial consciousness to appreciate the presence and influence of Himalayas.

6.2 Geographical and Geological Aspects

The Himalaya is the youngest mountain belt (20 to 60 million years BC) of the earth running in arcuate shape for about 2500 km between Indus & Brahamputra. It has more than 90 peaks above 6000m which displays several glacial and periglacial features. The geology of the Himalaya is very complex and intricate. The sediments comprising the rocks of Himalayas were deposited in a huge geosyncline which were uplifted, folded and faulted in various phases of mountain formation. Six major glacial and six inter-glacial stages have been recently identified in Karewa deposits (Jammu & Kashmir) based on lithological characteristics, field setting, faunal and floral assemblance and paleosurfaces (Pal, 1987).

The Himalayas extend from 35°N to 27°N latitudes and 72°E to 97°E longitudes. The Himalayan environment consists of the highest mountain system on our mother planet - the earth. Some of the highest peaks in the world namely Mt Everest (8848m), Kanchanjunga (8585m), Nandadevi (7817m) and Kamet (7756m) are located in Himalayas. The mountain system spreads over a length of about 2500 km in east-west direction and width varying from about 200 to 400 km in north-south direction. Usually, this mountain system is divided into three parallel longitudinal zones which have marked orographic features.

6.2.1 The Greater Himalayas

The main ranges rising above the snowline have an average elevation of 6100m asl. It consists of continuous series of highly fossiliferous marine sedimentary rocks of different ages.

6.2.2 The Lesser Himalayas

The middle ranges lie south of the greater Himalayas. These form intricate mountain system with an average height of 2600-4600m and are predominantly composed of crystalline and metamorphic rocks.

6.2.3 The Outer Himalayas

These comprise the Shiwalik ranges and lie between lesser Himalayas and the plains. The average elevation of this region varies from 1000 to 1300m and is composed of sedimentary river deposits.

Geological evidence exists that the Himalayas were formed by violent crumpling of the earth crust along the southern margin of the great table land of the Central Asia. The uplift of the Himalayas was a gradual process protracted over a long period from about 20 to 60 million years B.C. (Wadia, 1939). This process had a very marked effect upon the scenery, the topography and the river system. The principal rivers are of an age anterior to the tertiary earth movements and the drainage is spoken of an antecedent. During the slow process of uplift, folding and faulting, the rivers were able to keep largely to their original courses. The erosive power of these streams increased with increase in their bed slopes. Thus we find the rivers cutting through the main chains of ranges in deep transverse gorges after flowing for long distances parallel to the trend of the chain. Most of these rivers drain not only the southern slopes of the Himalayan mountains, but to a large extent, the northern Tibetan slopes as well. This results in watersheds not being located along the line of highest peaks but quite a distance north of it (Fig.11).

6.2.4 Principal Glacier-fed river systems

There are 22 major river system (Gulati, 1973). The important rivers which originate from the snow and glacier fields cover mountain catchment area of over one million Km^2 (Bahadur, 1987).

From Table 4, it can be seen that the mountain river systems of Indus, Ganga and Brahmaputra are differently glaciated. The average intensity of mountain glaciation varies from 3.4% for Indus, to 3.2% for Ganga and to 1.3% for Brahmaputra. The tributaries of these systems show wide range of glaciation intensity (2.5 to 10.8%) for Indus followed by Ganga (0.4% to 10%) and Brahmaputra (0.4 to 4%) but the average annual and seasonal flows of these systems give a different picture thereby demonstrating that the rainfall has differential effects demonstrating increasing effect of monsoon precipitation as we move eastwards from Indus to Brahmaputra.

6.2.5 High Altitude Lake system

In general, both saline and fresh water lakes exist in the high altitude region of Himalayas. The main chain of the high mountain forms a sharp dividing line between the humid region to the south which is influenced by summer monsoon and the arid northern flank where monsoon does not penetrate. Thus lakes extremely poor in electrolytes are abundant on one side whereas closed and saline lakes can be found frequently on the other one. Kashmir region abounds in glacial lakes which are situated well above the timber line at altitudes varying from 3500-4500m asl. (Zutshi, 1985). The lakes have been formed by embankment across the land of drainage by avalanche debris from a side slope or by the advance of a side glacier with its lateral moraines. In general, the catchment area of these lakes have scanty vegetation which is either scrub type or of some herbaceous species. The size of lakes vary from less than a hectare to several hundred hectares having depth from few metres to about 100 metres. The exact period of ice cover in these lakes is not very well known but it is generally presumed that ice melting starts by the end of June and lasts till October. The duration of ice free period of four months i.e. June to October can vary from year to year depending upon local weather conditions. The thermocline was found well developed in many cases but there is no information on the extent of thermal stability. The maximum surface water temperature does not exceed 15°C at any time during the summer. The hypolimnion water temperature was between 6-7°C in shallow water lakes. In some lakes no thermal stratification was observed and could be due to cold water inflowing from the adjacent glacier. High content of fine glacier silts in lake waters reduces light penetration and limits the depth and productivity of phytoplankton. The lake waters are also relatively poor in nutrient contents but are well oxygenated even at lower depth. Carbonate alkanity is usually absent in these lakes. The sediment analysis of lake waters show that they are sandy - type and poor in organic carbon. In some glacial lakes trout fish thrive well. Information about the catchment, ecological conditions including energy relationships need detailed studies. Most of the lakes in the central region are getting heavily silted due to landslides, deforestation and other human activities needing remedial action for the regeneration of their ecosystems.

Sikkim glaciers have large number of lakes and it is estimated from Landsat imagery dated December 31, 1987 that there are at least six lakes which have great disaster potential of causing floods in Tista River Valley (Kulkarni & Narain, 1990).

24 high altitude lakes in the Mt. Everest region have been investigated (Loffler, 1969). The altitude of these lakes vary from 4500-5600m well above the tree line at about 4200m and within the subnival belt. Most of the lakes were small with their maximum depth not exceeding 30m. The lakes dammed by glaciers disappear totally during the dry season in spring time and become re-filled during summer months (June to August). The annual amplitude of water level fluctuation ranges from less than a metre to 16 metres. Thermographic reading from about 10 cm depth indicate a maximum amplitude per day of about 3 degrees or less. All the measured thermal profiles are typical of cold monomictic lakes and no stable statification has been observed at all. Zooplankton in general is very monotonous and uniform in all of the lakes

investigated. Fish or any other carnivorous animals were totally absent, phytoplankton were extremely poor and no higher vegetation was found in any of the lakes.

TABLE 4 : PRINCIPAL GLACIER FED RIVER SYSTEMS OF HIMALAYA

No.	Name of River	Major River System	Mountain area (Km^2)	Glacier area (Km^2)	Percentage glaciation
1.	Indus	Indus	268,842	8790	3.3
2.	Jhelum		33,670	170	5.0
3.	Chenab		27,195	2944	10.0
4.	Ravi		8,029	206	2.5
5.	Sutlej		47,915	1295	2.7
6.	Beas		14,504	638	4.4
7.	Jamuna	Ganga	11,655	125	1.1
8.	Ganga		23,051	2312	10.0
9.	Ramganga		6,734	3	0.04
10.	Kali		16,317	997	6.01
11.	Karnali		53,354	1543	2.9
12.	Gandak		37,814	1845	4.9
13	Kosi	Brahmaputra	61,901	1318	2.1
14.	Tista		12,432	495	4.0
15.	Raidak		26,418	195	0.7
16.	Manas		31,080	528	1.7
17.	Subansiri		18,130	725	4.0
18.	Brahmaputra		256,928	1080	0.4
19.	Dibang		12,950	90	0.7
20.	Luhit		20,720	425	2.01
	TOTAL		1,001,294	25724	2.6

If one summarises the main features of the high mountain lakes, the change of light, temperature and in many cases of water level between dry and rainy seasons, due to the absence of monsoon, is most significant. This should provide for a striking annual rhythm not only in productivity but also in their faunal and floral composition which as a whole reminds much of northern extratropical lakes.

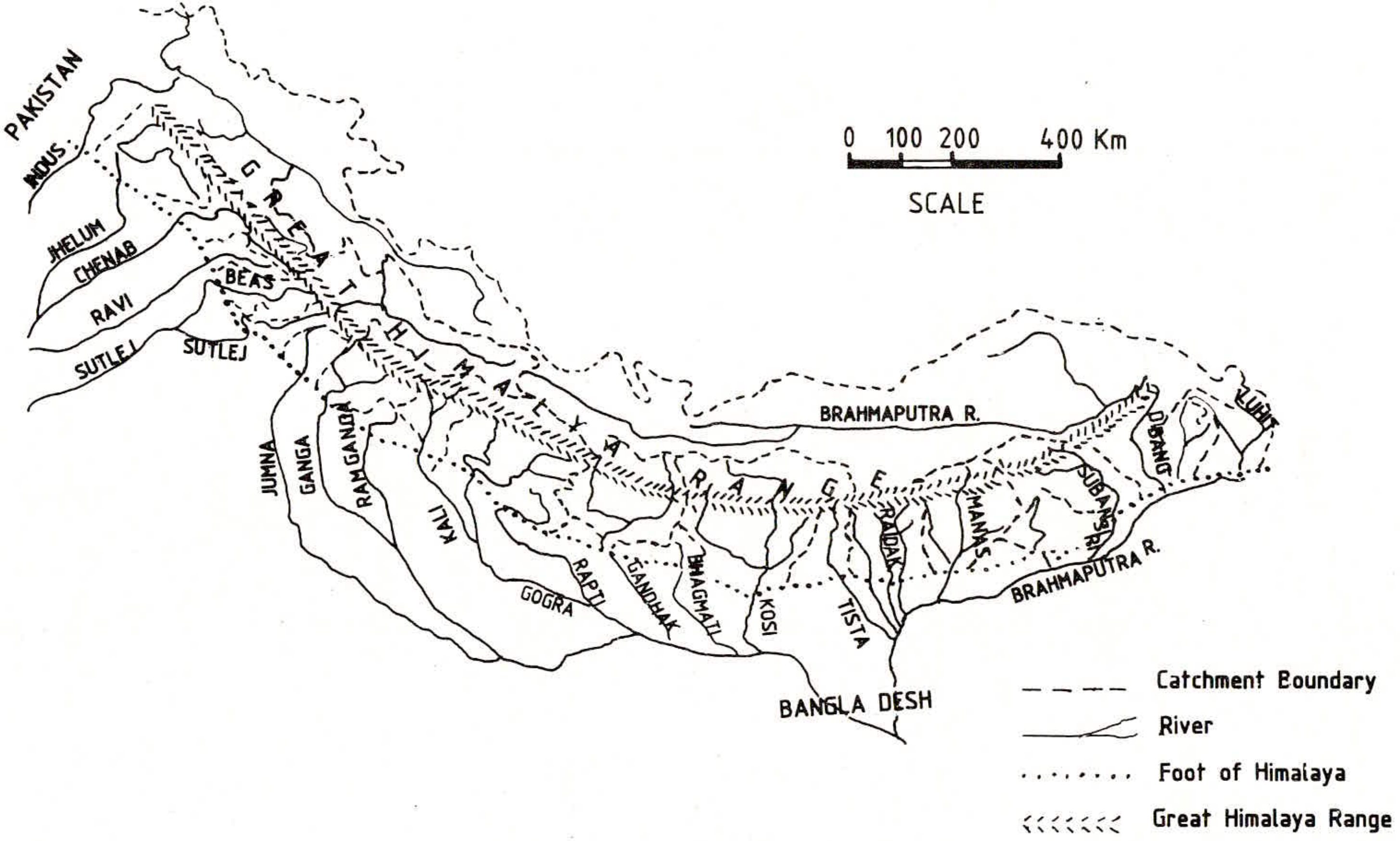


Fig. 11. Himalayan River Systems with their catchments.

6.3 Hydro-Meteorological Aspects

The Hydrometeorological characteristics of the Himalayan environment arise from its very high altitude attracting both polar and tropical disturbances. The Himalayan range has a dynamical and thermal influence upon the mid-latitudinal general circulation in the Northern Hemisphere and many believe that the Himalayan mountain affects the global climate (Bahadur & Datta, 1989).

In general, there is a great variability in all the meteorological parameters observed in this environment of complex relief. The complexity of the relief features as well as differential effect of the weather systems in different regions are responsible for generating a variety of climatic patterns observed in Himalayas.

The precipitation over mountainous areas are governed by (i) direct uplift of the air, (ii) stimulation of convection, (iii) general storm precipitation and (iv) spillover. The direct lifting of the air by a mountain leads to adiabatic cooling which produces rain. In the case of stimulation, conditionally unstable air on encountering a mountain slope gets lifted up beyond its instability level, and causes convective precipitation. General storm precipitation from such weather systems as cyclones etc. produce precipitation from dynamic interactions which lead to convergence of air and cause consequent lifting. In such cases, precipitation can occur whether mountains are present or not. This type of precipitation is called the convergence component of storm precipitation that falls on the lee side, after having been formed on the windward side and being carried by the wind stream on the lee side before it reaches the ground on the windward side.

The characteristics of precipitation are also influenced by increasing altitude (orographic precipitation in three ways (Bahadur & Upadhaya, 1982).

i) The quantity of precipitation increases with altitude upto a certain level and decreases thereafter. The level of maximum precipitation varies greatly from place to place depending on local topography.

ii) Average variability of precipitation generally increases with altitude.

iii) On high altitudes, the maximum precipitation occurs generally earlier than on the foothills.

The studies conducted in the neighbourhood of Mount Everest have shown that the rainfall regimes have a pronounced monsoon character (Miller, 1965). The Himalayan mountain system functions as a great climatic divide which exerts a dominating influence on the meteorological conditions of the Indian sub-continent to its south and the Central Asian areas to the north. In winter months, the Great Himalayan Range serves as an effective barrier to the intensely cold continental air blowing southwards from Siberia into India. During monsoon months it forces the rain bearing winds up the mountain to deposit most of their moisture on the Indian side.

It is believed that the maximum precipitation in the Himalayas is obtained near Shiwalik ranges located at around 1200m elevations and the higher regions are less precipititous. Recent investigations show that there exists no linear relationship between elevation and mean precipitation and the two could be best related by a polynomial of the 4th degree (Dhar, 1976).

As a general rule, the maxima of precipitation has to be located fairly close to the equilibrium line and the annual precipitations are great even under extreme continental climatic conditions (Kotlyakov, 1972). Hence, we can surmise that the areas of maximum precipitations lie in the Great Himalayan Range. A simplified orographic model of precipitation (Bahadur, 1987) in Himalayan environment is shown in Fig.12.

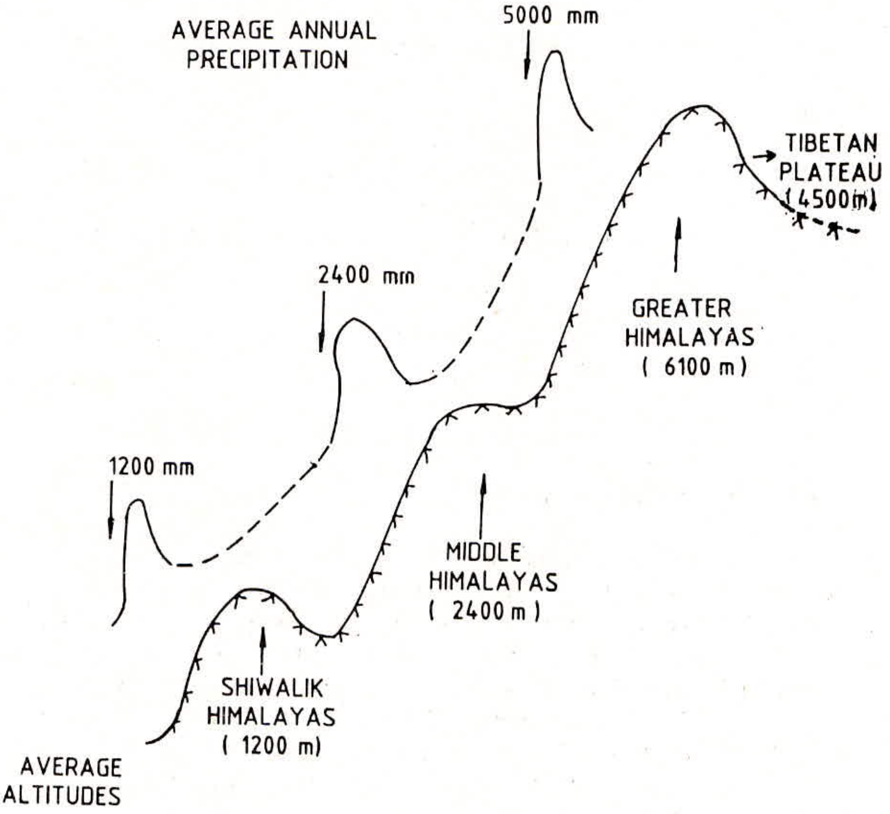


Fig. 12. Simplified orographic model of precipitation in Himalayan Environment.

6.4 Seasonal Snow Cover

The importance of snowfall and seasonal snow cover on Himalayan mountain during the winter months was recognised as early as 1875 by Gibert Walker for a proper understanding of the meteorology of India. Qualitative information is being collated by collecting monthly information received from District Officers, Forest Officers, Officer Incharge of Mountain Passes, Travellers, etc. Their reports usually contain information on the number of days on which snow fell and a rough estimate of quantity of snow fall during a month; the thickness of snow cover on certain passes and stations at the end of month, the lowest altitude to which snowfall reached during the month and a qualitative comparison of the snowfall in the month with that of a normal year. The data suplied are in the nature of estimates and often incomplete because the persons who supply the information as well those who record them are not trained personnel (Banerji, 1956). Even this fragmentary data for long series of years had been found quite useful (Gowariker et al., 1989).

Systematic studies on snow precipitation and seasonal snow cover are of recent origin and have commenced from 1969 onwards with the establishment of Snow and Avalanche Study Establishment at Manali of the Defence Research Development Organisation.

The occurrence of snowfall during winter months is due to the influence of low pressure systems of extra-tropical origin from West to East (Western disturbances). These western disturbances are characterised (Mohan Rao, 1985) by one of the following forms:

i) Depression or well marked low pressure area at the surface associated with upper air cyclonic circulation.

ii) Feeble low pressure area on the surface charts.

iii) Upper air circulation or troughs.

In general, the snow precipitation decreases and seasonal snowline moves to higher altitude as we move from west to east in the Himalayan region. The observations show around 30 Western Disturbances in a winter season move over Northern India with an average frequency of 5 to 6 disturbances a month. The snowfall is highly variant in the space and time and it occurs in spells or storms spread out generally over a period of four months. On an average 13 spells occur in a winter. The duration of individual storms varies from 1 to 7 days, most frequent duration being of 2 days. It has also been observed that there were 83 occasions out of a total of 168 when the individual storms lasted for more than three days.

Sometimes, the intensity of snow fall in individual storms may be more relevant and important than even the total snowfall as the rapidity with which the mountain slopes gets loaded has a direct effect on the stability of a snowcover. Intensities as high as 3 to 4 cm/hr. are commonly observed in this mountain region.

It has been experimentally demonstrated that it is the temperature alone and no supersaturation of the surrounding vapour that governs the crystal form. The observations made at an altitude of about 2500m in the Pirpanjal range indicate that plates, stellar crystals, needles and columns are rarely seen. The predominant types appear to be dendrites, irregular crystals and graupel.

It may be stated that in spite of considerable experimental and theoretical work, the physical mechanism underlying the formation of intricate snow crystals are still largely unknown.

A typical variation of snow density as observed in western Himalayas with depth and time is shown in Fig.13.

The following features can be observed:

i) the snow density increases with the advancement of season and with depth;

ii) variations in density reduces in the late winter or spring months.

It is also observed that the melt metamorphism is more predominant on slopes facing towards south than on those facing north (Upadhya, 1981).

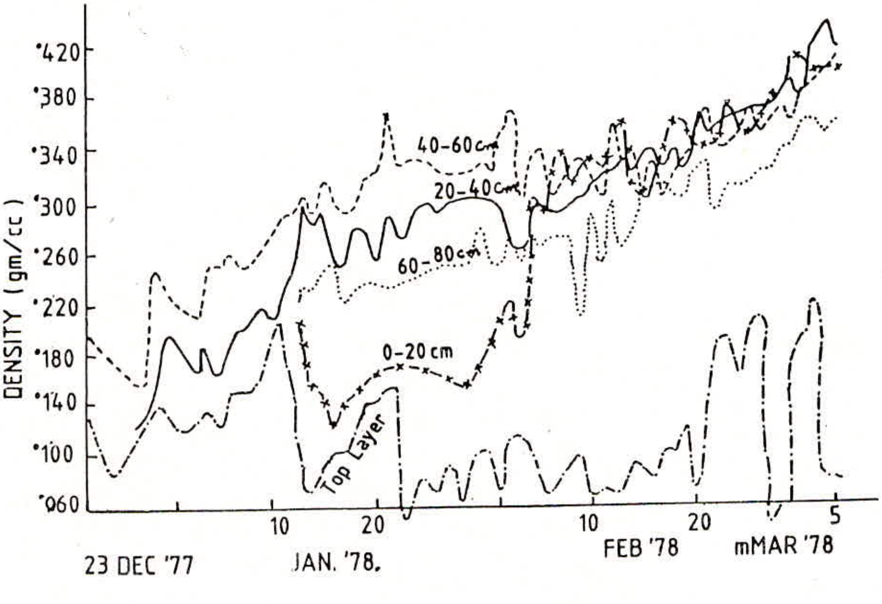


Fig. 13. A sample variation of snow density with depth and time.

6.5 Glacial Cover

Presently, glaciers occupy an area of 14.9 million Km^2, which is about 10% of the world's land area. Although only 3% of this permanent snow and ice is situated over mountains outside the Polar regions, this relatively small amount is of great importance because of its proximity to populated areas (Meier & Roots, 1982). The existance of these snow and ice fields is important not only as a source of water and power but also in connection with the development of tourism and the great moderating influence on the climate.

For over two million years glaciers have sculpted the earth's landscape and largely influenced the course of human history in various parts of the world. Indo-Gangetic Plains, being the legacy of ice age due to glacial action such as erosion, deposition, retreat and advance, the arable alluvial soils (composed of loess - windblown silts and clays) have retained their fertility for over thousands of years.

Glaciers of high Asia cover an area of about 50% all glaciers outside of the polar region and they contain approximately 33 times the areal cover in European Alps (Wissmann, 1959).

The data collected on Himalayan glaciers for several decades indicate a continued recession of glacier snouts indicating negative mass balance of these glaciers. The observations on retreat for the glaciers in the Himalayas are tabulated as follows from 1845 onwards (Vohra, 1978).

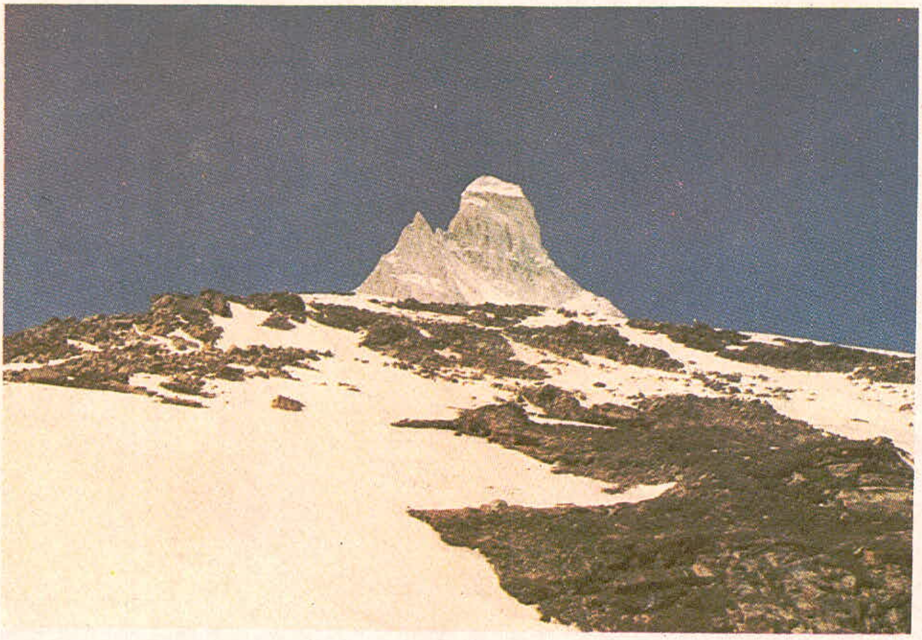
TABLE - 5 THE RETREAT OF GLACIERS IN THE HIMALAYAS

Name of the Glacier	Periods	Years	Retreat in metres
Zemu	1909-1965	56	44
Milam	1849-1957	108	1,350
Pindari	1845-1966	121	2,840
Shankulpa	1881-1957	76	518
Poting	1906-1957	57	262
Glacier No.3	-	-	-
In the Arwa Valley	1932-1956	24	198
Gangotri	1935-1976	41	600

Rate of recession of Gangotri glacier since 1935 is shown in Fig.14. The rate of retreat kept on increasing between 1935 and 1971, it has rapidly decreased since then and the glacier is expected to come to a standstill soon (Vohra, 1981). Panoramic view of Gangotri glacier is shown in photographs P-1 to P-7. The coloured photographs are taken from the report from Wadia Institute of Himalayan Geology (Chaujar and Choudhry, 1986)

P-1 GANGOTRI VALLEY GLACIER - ITS INTERSECTION WITH KIRTI BAMAK - A LEFT BANK TRIBUTARY (PHOTO WIHG, 1986).

P-2 GAUMUKH - THE SNOUT OF GANGOTRI GLACIER (DARK ICE) WITH BHAGIRATHI PEAKS IN THE BACKGROUND (PHOTO WIHG, 1986).



P-3 SHIVLING, AS VIEWED FROM UPPER TAPOBAN (PHOTO WIHG, 1986).

P-4 ICE-STRATIFIED DRIFT CONTACT ON GANGOTRI GLACIER, BLUES ARE THE WATER BODIES ON THE GLACIER ICE (PHOTO WIHG, 1986).

P-5 LONGITUDINAL AND TRANSVERSE CREVASSES ON THE GANGOTRI GLACIER NEAR SNOUT PORTION (PHOTO WIHG, 1986).

P-6 LAKE FORMED BY DAMMING OF DRIFT AND OTHER DEPOSITS (PHOTO WIHG, 1986).

P-7 GLACIER ERRATIC ON KIRTI BAMAK - A TRIBUTARY OF GANGOTRI GLACIER (PHOTO WIHG, 1986).

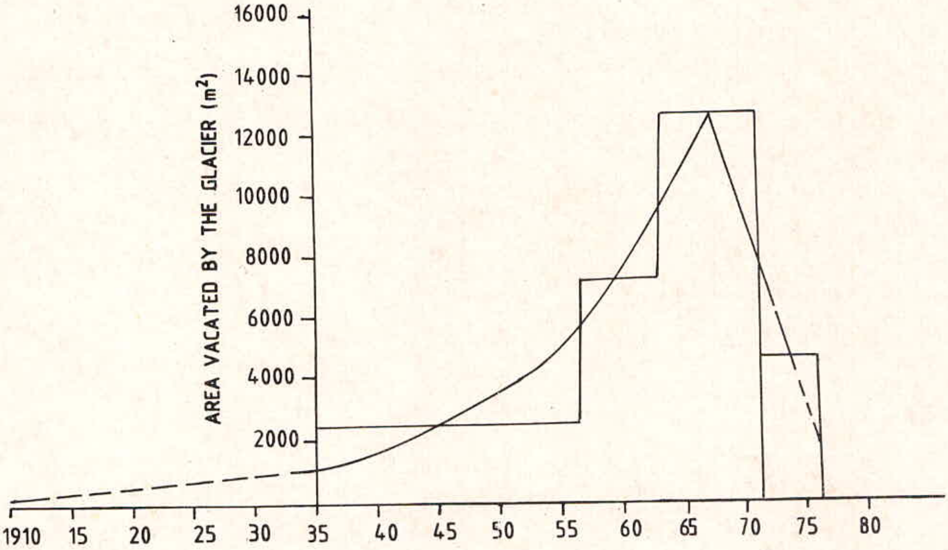


Fig. 14. Rate of Recession of Gangotri glacier.

Historical records of fluctuations of glaciers in Himalayas and trans-Himalayas date back to the early nineteenth century but the records are widely distributed. However, a good account covering regional synthesis of 112 glaciers since 1812 has been reported (Mayewski & Jeschke, 1979). In a gross sense Himalayan and trans-Himalayan glaciers have been in a general state of retreat since 1850.

The glaciers fluctuations are normally categoried as secular, long-term, periodic, short-term, seasonal and accidental depending on the glaciers movement. Some of the catastrophic advances are believed to have occured primarily due to earthquakes. There are surging type of glaciers which advance suddenly are known to occur in Karakoram Himalayas. There are glaciers which block the river channel creating impounding lakes which when bursts create devastating floods. Other neteworthy observations about Himalayan glaciers as reported by these investigations are:

- Khumbu glacier in the Everest region is reported to be stationary from 1930 to 1956 though the glacier thinned approximately 70m under a thick debris cover.
- Pindari glacier and Garwal region have undergone the greatest retreat of any glacier in the Himalaya. Total retreat since 1850 has been 2600m.
- In Lahul Spiti region (Bara Shigri - a transverse glacier) rates of retreat varied from 62.5 m/yr during 1890-1906 to 20.5 m/yr during 1906-1945.
- South side of Karakoram contains several surging glaciers. It is reported that Garumbar experienced a 2.5 km. advance between 1892-1925.
- Yinguts glacier surged 3.2 km in eight days during 1902/3 and Kutiah glacier surged twelve km in two months in 1953.
- Surging glaciers blocked the course of Shyok river at several times creating upstream lakes. Subsequent bursting of these dams have resulted in flood havocs and create devastation to the downstream population.

The glacial area of Central Asia mountains is over one million Km^2 (Flint, 1971) and out of this over 50,000 Km^2 of the areas is covered by glaciers which drain into Himalayan rivers (Bahadur, 1987). An exact inventory of these Himalayan glaciers is not available. From time to time there had been some inputs and efforts in this direction (Karpov & Kirmani, 1968, Muller, 1970, Vohra, 1978, Raina, 1984, Dhanju & Kulkarni, 1987, 1988, Kulkarni, 1989, 1990 & 1991) but a lot more effort is needed to complete the inventory of the glaciers in this region.

Remote Sensing based inventory of glaciers using IRS LISS-II & Landsat TM images are prepared (Kulkarni & Dhanju, 1987, Kulkarni 1989, 1990, 1991). Glacier features e.g. glacier boundary, ice divide, snow equilibrium line, ablation area, accumulation area and glacier lakes are mapped based on the follow characteristics on the FCC's (False Colour Composite) in scales varying from 1:250,000 to 1:50,000 using Large Format Optical Enlarger (Fig.15).

TABLE 6 : IMAGE CHARACTERISTICS USED FOR IDENTIFICATION OF GLACIER FEATURES

Feature	Tone	Remarks
Accumulation area	White	Glacier snow exposed.
Ablation area	Green blue	When ice exposed, edges characterised by dirty snow.
Ice divide	Black	Associated with cliff shadow.
Glacier lake	Dark blue to back	Depending upon lake depth and sediment content

Other snow/ice and glacier features e.g. permanent snow fields, ice aprons and rock glaciers could not be mapped as these require digital analysis or multitemporal data. The salient results are given as follows:

TABLE 7 : REMOTE SENSING BASED GLACIER INVENTORY

State	No.of glaciers	Area Km^2	Volume Km^3	
			Ice	Water
H.P.	125	1896	190	165
U.P.	133	2837	285	248
Sikkim*	25	431	51	44

**With six lakes covering an area of 5.9 km^2 which could be categorised as unsafe and could cause disastrous floods. Prominent ones are on Lonak and Tista Khangs glacier.*

The accumulation area ratio (AAR) derived from the above studies demonstrated that the Gangotri glacier mass balance was negative for the hydrologic year 1987-88 (Kulkarni, 1989). The total ice volume in the Himalaya is estimated to be around 1400 km^3 (Vohra, 1981) which could be higher by a factor and needs to be re-assessed.

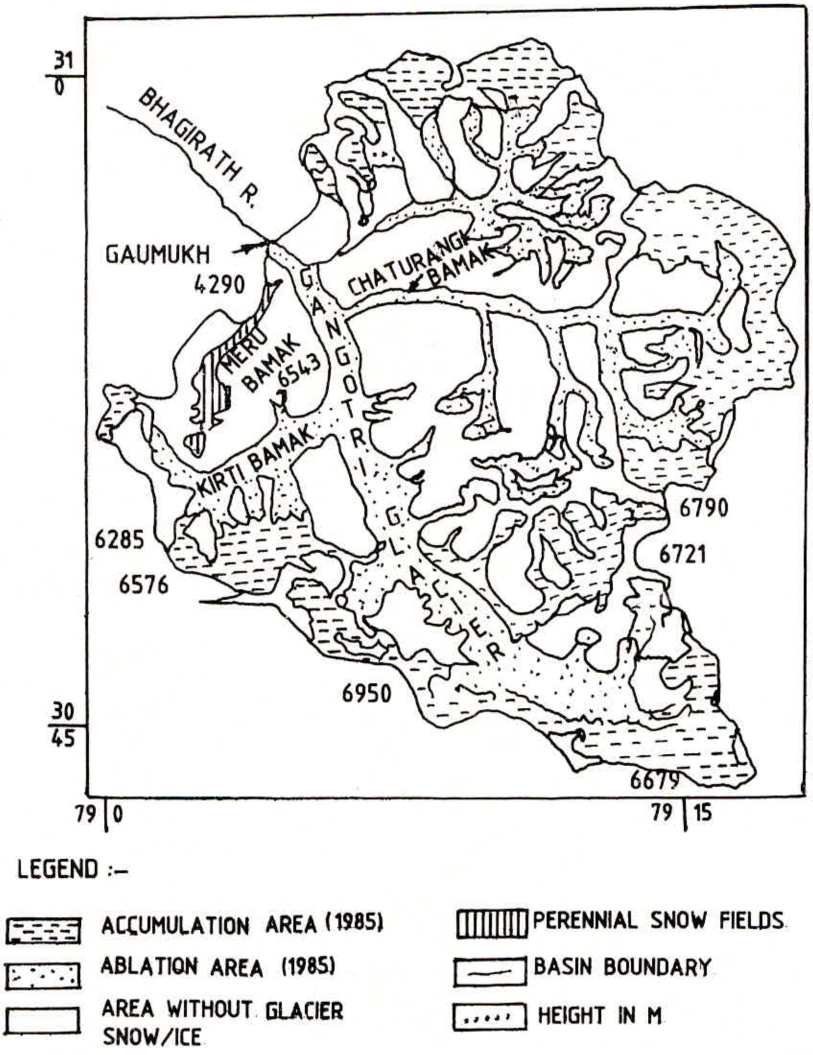


Fig. 15. Remote Sensing Inventory of Gangotri glacier.

(SOURCE : KULKARNI, A.V, 1989)

The Himalayan glaciers numbering around 15,000 form a unique system in the Eastern Hemisphere. The large expanse of glacier cover over Himalayas - a criss-cross chain of mountain ranges contains glaciers with different orientations and elevations thus adding complexity to the study of the environment.

These glaciers are located on a steep altitudinal gradient between the Tibetan Plateau to the north and the Indo-Gangetic Plain to the south. Vertical drops in elevation as great as 300 m/km. over 25 km., as exemplified in the NANGA PARBAT region, are not uncommon (Wadia, 1989).

These glaciers have a large variation in their size and are found to have occupied small recesses at high altitude to enormous ice flows which could rival those existing in polar circles. In general, the glaciers descending transversely to the strike of the mountain are shorter in length. Their snouts fluctuate more abruptly and they descend to lower levels (2150m). On the other hand, the longitudinal glaciers - moving in a direction parallel to the strike are less steep and less sensitive to the variations of snouts and these rarely descend to altitudes lower than 3100 m. These could be broadly classified as predominantly monsoonal (Eastern Region), equal to subsequent monsoon (Central Region) and dominant winter precipitation (Western Region) based on presently prevailing hydrometeorological conditions (Vohra, 1978).

Geomorphologically, the Himalayan landscape can be classified as transitional between youth and maturity. Complexly folded slopes are replaced by the concave profiles of converging cirque basins formed during various glaciations that affected the area. Some suggest as many as five Pleistocene glacial advances while others four or even three or two (Ahmad, 1982). The picture is not clearly demarcable but one fact is clearly brought out that all the present and Pleistocane glaciers as well as snow lines are lower in Western Himalayan than the Eastern Himalayas. This may be predominantly due to latitudinal differences of the two area.

Glacio-geomorphic studies do provide a first order climatic interpretation; they do not provide a direct approach as is the case with the glacio-chemical studies for a period of few hundred years. Lately, some adhoc investigations (Nijampurkar & Bhandari, 1982 and Nijampurkar & Rao, 1989) have been performed in Kumaon, Kashmir, Ladhak and Sikkim Himalayas to find the origin of precipitation, dating of snow and extent of pollution of the environment but it is not possible to make any specific statements about the behaviour of glaciers on seasonal basis except that the potential of applictions of various technologies has been established. More systematic work is needed on selected glaciers about their seasonal and long-term behaviour.

6.6 Assessment of Melt Water Contributions

Basic requirements for understanding and proper management of high-mountain water resources includes knowledge of the amount and location of stored frozen water, the patterns of water release by melting, and how these patterns of release depend on short-term weather and long-term climatic change.

In glaciated regions, studies have been directed at a better practical use of water discharge observations recorded in mountain basins. During the last decades runoff amounts in general could have been higher compared with what they would have been releasing during periods of steady state glacier conditions. This is attributed to glacier shrinkage due to general warming of the global climate (Ostrem, 1972).

It is necessary, therefore, to correct present discharge observations in order to obtain "Normal" annual means. Such corrected means can be used to compute the annual average specific discharge (commonly expressed in litres/sec/km^2 and to construct isohydats lines through points of equal specific discharge. Hydroelectric power planning in high-mountain areas is generally based upon isohydat maps and their construction is therefore, of vital concern and should be undertaken by Central Water Commission and Central Electricity Authority.

Further rheological (ice movement) studies on the glacier surface should be conducted as these are dependent both on the local environmental setting and on the prevailing meteorological conditions.

Discharge from a glaciated region is an integrated output of a number of meteorological parameters; these include liquid precipitation, air temperature, incoming radiation, air moisture and wind velocity. The meteorological approach considers the mass/heat exchange at the glacier surface and has achieved a fair degree of success in forecasting snowmelting and glacier drainage. Models have been developed for short-term runoff forecasts and they give reliable results for 1-3 days in advance. Good weather forecasts can extend this period (Bahadur and Datta, 1989). In principle, there are two different methods presently in use: a physical model based upon energy exchange at the glacier surface: and a mathematical statistical model based upon actual observations of runoff and meteorological parameters. Actual glacier runoff volume may vary from ± 20 to ± 30 per cent from the normal annual discharge (Ostrem, 1972). The mean glacier elevation is found useful for study of the glacier-climate relationships.

Glacier melt processes are less complex than snowmelting as entrapped air plays a relatively smaller role. In general, glaciers have typical hydrological characteristics because of the changes which they undergo in their physical properties during different seasons of a year. In general, a glacier builds up during winter and depletes in summer and spring months. Glacier run-off is minimum in the early morning and maximum in the late afternoon. As the air temperature rises, the top snow surface on a glacier begins to melt, meltwater starts percolating through the snowpack and finds its way to the body of the glacier through crevices; this process also assists in the melting of aditional ice. This discrete conduit system changes continuously by melting and plastic flow of the ice. A constant supply of heat from the bedrock adds to the melt contribution of glacier ice. Pressure melting also takes place in the body of a glacier system. Calving depletes the mass of a glacier. Sometimes glacier streams show sudden and unexpectedly high discharge due to glacier bursts-jokulhaups (Bahadur, 1981).

Glaciers are generally out of equilibrium with their environment, they are eithe retreating or advancing. If retreating, frozen water is being removed from storage and consequently, yearly streamflow will be more than that derived from precipitation alone. Thus, streamflow records obtained during periods of recession cannot be considered normal as there will be much less water supply in the case of glacier advance. It has also been observed that the mass balance at points on mountain glaciers vary more with altitude than with any other parameter and this is commonly used to determine the activity of the glacier but it also depends on glacier size and local topography.

It has been observed that the river discharge of Himalayan snow fed river of a unit area is roughly twice that of penunsular rivers of South India. This is mainly due to perennial contributions from snow melting and glacial drainage.

Hydrological characteristics of glacial streams of Punjab rivers were outlined (Kanwar Sain, 1946). Immediately after independence, Dr. Church, President of International Commission on Snow and Ice was invited by Government of India in 1947 to initiate snow surveys with a view to forecast stream flows in snow and glacier fed river system (Dhir & Singh, 1956).

In absence of systematic observations of snow, the available qualitative data of snowfall for 70 to 80 years was a subject to study for study of snow melt of Sutlej basin (Bahadur, 1973). It was observed that the snowfall was best related with the longitude, thereby showing the effect of strong westerly winds of winter precipitation. Another attempt was made to co-relate the specific yield with the percentage of snowfall in the total precipitation for Chenab River System (Bahadur et al, 1978). The data consisted of precipitation from 25 hydrometeorological stations and streamflows at 11 different gauges and discharge locations. The analysis of data showed that the total annual precipitation is poorly related with the elevation but ratio of rainfall to snowfall decreases with the increase of elevation. The water yield increases with the increase in the percentage of glaciated area ranging from 0.95m to 2.16m for 14% to 72% of glacier cover in the catchment. The correlation coefficient between the sediment yield and runoff is very strong (r=0.98) for snow and glacier melt contribution. Daily snow melt runoff for Beas River catchment upto Manali making use of the areal snow cover information from Landsat imageries for the period April to July, of 1971 to 1976 with snow cover depletion curves for six years are shown in Fig.16 (Jeyram et al, 1985). A close examination of these curves show that the snowcover depletes slowly in the month of April to mid May but the depletion is fast during later May and June. A comparison of these curves indicate similarity in shape but shift in time. The time shift is a function of the volume of stored snow in watershed. The prime factor controlling the slope of the depletion curve is climatological regime imposed on the basin during the melt period. Energy balance model of snowmelt for use with routinely collected meteorological data and produced nomograms based on this model (Daco & Shirvalkar, 1985). The authors have also tried to establish delay periods for a snowmelt water to reach gauging point and it is claimed their estimates using the nomograms compare favourably with the observed data for the catchment for clear or partly covered sky conditions. However, the nomograms under estimate by a factor of three for overcast condition or near overcast condition. An approach for estimation of maximum water equivalent of snow cover in the catchments and time distribution of snow melt from April to June was presented (Abbi et al, 1985) using features like area elevation relationships, freezing level, surface temperature and snow lay factor. Monthly snow melt have been computed using degree day concept and compare with actual discharge observations at Kulu with a purpose to evolve relationship in forecasting river discharge on the basis of snowmelt. Model results of daily snowmelt runoff during pre-monsoon months using information regarding the areal extent of permanent and temporary snow cover obtained by comparison of a few available satellite imageries and considering altitude effect on temperature, orographic effect on precipitation, melt due to rain, losses from melt water and effect of rain falling on snow cover area was presented (Seth, 1985). A study based on 1981-82 ground data collected by SASE - team from a snow cover located in Beas catchment using Point energy and mass balance techniques have been utilised to generate the melt runoff (Agarwal et al, 1985). Results presented demonstrate the relative merits of energy and mass balance methods over the conventional degree-day-method. The authors have emphasised the importance of undertaking detailed snowmelt runoff studies with a view to develop and evolve appropriate simulation models for the environmental conditions existing in the country. The status of snowmelt runoff assessment and forecast using satellite data was presented in the national symposium (Ramamoorthi, 1985).

Though no definitive conclusions can be drawn from available studies, the annual contributions to streamflows from ground snowmelt (March-June) may be roughly estimated aroung 20% while the melt contribution of snow on glacier ice during July-September may be about 50% of the annual stream flow respectively. It may be noted that the later component of snowmelt contribution continues throughout the year making the rivers perennial. The period from April to September is accelerated snowmelt period contributing large inflows to the streams while October to March is the period when snowmelt is delayed and its contribution to the annual volume is small.

The average annual streamflows of the snowfed river systems are :

INDUS RIVER SYSTEM	206 Km^3/yr
GANGA RIVER SYSTEM	488 Km^3/yr
BRAHMAPUTRA RIVER SYSTEM	510 Km^3/yr

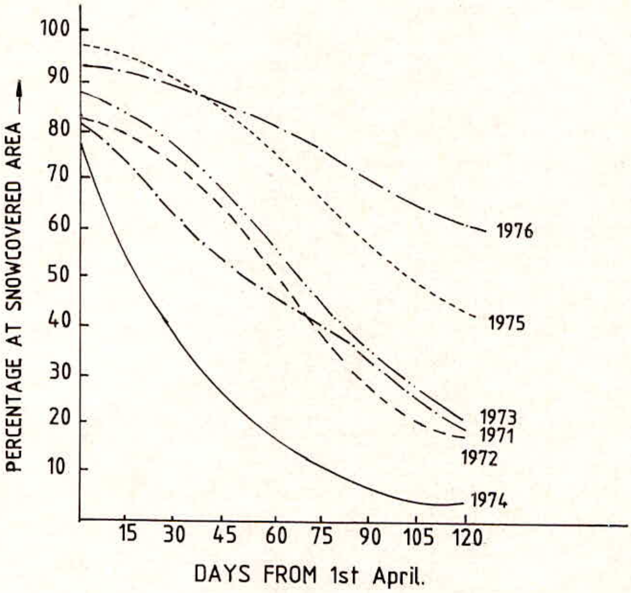


Fig. 16. Snowcover depletion curves as derived from Landsat imageries.

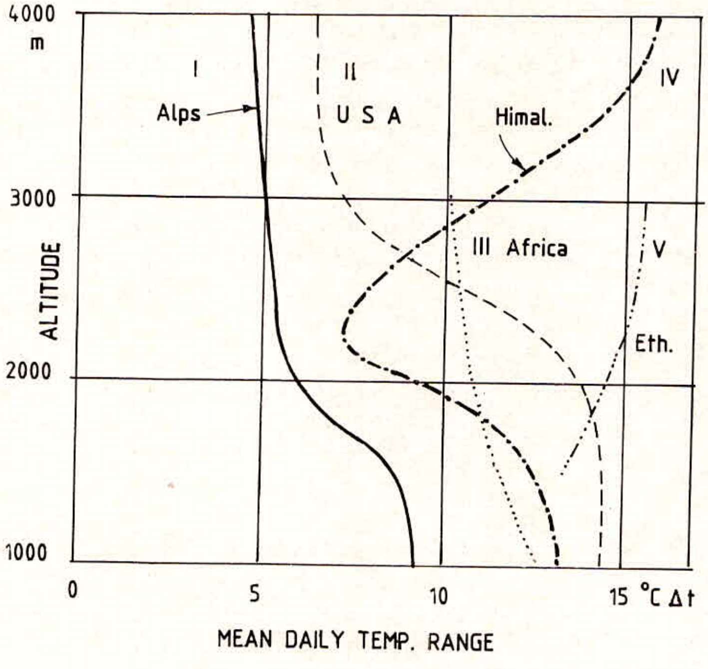


Fig. 17. Mean daily temperature range versus altitude in different mountains and highlands area pointing out uniqueness of Himalayas.

What is not clearly understood and appreciated is that the major part (70 to 80%) of all the snow and glacier melt runoff comes during the months of June-September when the monsoon is active at lower reaches.

In order to make a better utilisation of the snow and glacier melt water, we have to go in for making reservoirs in the high mountain region upto 3000-4000m (Bahadur, 1987). Luckily we have hard and good rocks at these elevations. We can have a cascade system of reservoirs so as to provide fuller benefit for hydroelectric power generation to the colder and underdeveloped region of the country. The planning for optimal utilisation of this water resources has to include the concept of the runoff river schemes with limited reservoir capabilities, as creation of large reservoir capacity may be relatively more expensive and hazardous in seismically active region. The presence of high altitude reservoirs will help alter the thermal regime of the region and thereby contribute for improving the health of glaciers and save them from excessive melting and recession. Such an approach shall help preserving the enormous snow and ice reservoirs whose presence create various microclimates affecting regional climate and the climatic change of the subcontinent.

Utilisable water resources of the entire country has been assessed to be 666 Km^3/yr. (2nd Irrigation Commission, 1972) but this figure is further modified by National Commission on Agriculture evaluating the utilisable potential to be 700 Km^3/yr. The projections for progressive utilisation (National Commission on Agriculture, 1976) is made as 380 Km^3 (1974 A.D.), 750 Km^3 (2000 A.D.) and 1050 Km^3 (2025 A.D.). This shows that the requirement is going to exceed the available resources. Hence, we do require a radical approach for water resources planning from Himalayas keeping in mind that the water demand roughly increases twice as rapidly as does the population and the Himalayas are the unique feature on our mother planet (Fig. 17).

7. SOME PERTINENT OBSERVATIONS

This chapter contains futuristic aspects connected with the threat to glaciers due to impending climate change, artificial regulation of snow and ice melt, strengthening of high altitude observation network and the knowledge gaps to be filled in view of technological advances made elsewhere in the world.

7.1 Threat to glacier due to climatic change

During the past five billion years our planet, the earth has experienced recurring ice ages, starting roughly 650 million years ago (Bahadur, 1989). Four such ice ages have already passed and the earth is heading to experience the fifth ice age. Several hypothesis have been propounded for recurrence of an ice age. e.g. wandering of poles, reduction in CO_2 of the atmosphere, earth movements resulting in profound uplift, eruption of volcanic gases, drifting of continents, changes in the ocean water circulation, variation in solar radiation, etc. But the exact cause for recurrence of ice age is not yet fully known.

The climatic variability in space and time is of great importance to human beings, plants and animals. The physiology and behaviour of all organisms are generally adapted to such as a variability in due course of time. The climatic variations of different origins and duration as understood today are given in Table - 8.

TABLE 8 : CLIMATIC VARIATIONS (LANDSBERG, 1976)

Term years	Duration	Known or potential origin
Climatic Revolution	›10^6 -	- Geotectonic activity e.g. Continental Drift, Orogeny, large scale changes in land/water distribution-possibly solar variation.
Climatic Change	10^4 - 10^6	Changes in solar emission and extra-terrestrial isolation due to long period changes in orbital elements.
Climatic Fluctuation	10^1 - 10^4 -	**Aperiodic**-volcanic activity - **Quasi-periodic**-changes in solar emission (sunspot rhythms), magnetic declination, slow deep ocean current, terrestrial feedback mechanisms.
Climatic Interaction	‹10	- Very short-term quasi-periodic natural variation. - Quasi-Biennial Oscillation (2-3 yrs.) - Possible atmosphere-ocean interaction
Climatic Alteration	-	- Anthropogenic causes - effects can be global/regional/ sub- continental or local in scale. **Global** - Increases in atmospheric concentrations of CO_2, NO_x, Halocarbons and particulates. **Regional** - Power production, industrialisation, urbanisation, clearing of vegetation. **Local** - Urbanisa tion, agricultural practices, grazing, water storage, deforestation/afforestation.

Ice-core studies have been helpful to resurrect past climatic changes for over 100,000 years B.P. It has shown evidence to well-known recent past events as the temperature maximum during 1920s and 30s. The little ice age of 17th and 18th century and the warming period between 550 and 1150 A.D. At ten thousand years B.P., the 18° content fell rapidly corresponding to the final stages of last glaciation (Bahadur, 1985).

Let us recall the evidence which suggests that the climate has fluctuated between rather wide temperature limits upto 15° C for hundreds of millions of years. While these limits are large enough to have had major influences on species extinction and evolution and large enough to encampass glacial and inter-glacial ages. There does not seem to be much chance that earth is vulnerable to a run-away greenhouse effect as on Venus in which ocean would boil away or to a cold catastrophe on the Mars, no matter what we would do in the next century. Still climate changes as great as an ice age would almost certainly be disasterous for humanity if they occurred rapidly (Schneider, 1989).

The concentration of trace gases in the atmopshere have continued to increase for the last few decades. Presently, the contribution of CO_2 to global warming is roughly estimated as 50%. The other 50% is attributed to trace gases such as methane, CFC, N_2O and O_3 . Over the past 15 years, the rate of accumulation of CO_2 is the atmopshere has been about 1.5 ppm/yr. The atmosphere is already committed to a warming of 0.7 to 2°C due to emission of greenhouse gases upto early 80s. At the current rate of emissions, the global warming will increase by 0.2 to 0.5°C every decade and by the end of this century the accumulated surface warming will be large enough to rise above the background climatic fluctuations. When this happens the existing glaciers are supposed to melt more rapidly flooding the land and raising the sea level submerging large tracts of coastal areas, etc. These changes may again bring in some stability in the earth atmopshere system as glaciers,by virtue of their own inertia, may act in slowing down the rate of change of climate, in the glaciated region. As there are several interacting factors which help in self-adjusting the environment of land, sea and atmosphere, no definitive conclusions could be drawn with any confidence as the global modelling efforts are still in their formative stage to address to the complexities of various feedback mechanisms of the natural system.

7.2 Artificial Regulation of Snow and Ice-melt

Induced snow melting has been in use for clearing snow on highways. This is achieved by heating (from solar energy, burning of combustible substances or using a centralised heat source) or by spreading chemicals on snow surface.

Coating the snowcover by dark materials (coal, dust,soot, industrial slag or finely powered organic matter) results in reduction of albedo thereby absorbing more solar energy for rapid melting.

The use of chemicals is based on the principle that the lowering of the vapour pressure of the solution formed by adding the chemical to the snow lowers the freezing point of water. Readily available and low cost salts e.g. rock salt, Nacl & $Cacl_2$ are particularly useful. Generally a mixture of two salts with addition of cinders, sand or gravel is used.

Investigations conducted have shown augmentation of 2-4 mm of water/day for about a week by spraying about 400/gm/m² of coal dust (USSR) or 20 gm/m² of lamp black (USA). It is reported that pollution and logistic problems are considerable with very infavourable cost-benefit ratio. Further the melting effect peters off after about a week.

Experiments (DST, 1976) performed in India during 1975 have given the following results:

- GSI conducted three different experiments with coal dust layer ranging from 400 gm/m² to 1600 gm/m². The results indicated an increase in melt by about 50% with 400 gm/m² over three days.

- SASE used coal dust and soil mixture of 216 cc/m², 432 cc/m² and 792 cc/m² (roughly equivalent to 300 gm/m², 600 gm/m² and 1100 gm/m²). The spreading of 216-432 gm/m² resulted in 60% additional melting with coal dust and 40% additional melting with soil mixture. It was also observed that the disturbed snow melted much faster i.e. upto 300% more than undisturbed snow.

7.3 Strengthening of High Altitude Observation Network

Normally there should be one observatory for snow cover monitoring for each thousand to ten thousand square kms. of area. The observatory should be manned by a team of trained personnel and equipped with instruments capable of observing most of the hydrological parameters such as discharge, snow depth, density, stratigraphy, etc. and meteorological parameters such as precipitation, temperature, radiation, albedo, humidity, wind, etc. Sets of portable equipment and snow-kits are necessary for snow surveys and mass balance observations. Under the manned observatory there should be a number of part time or subsidiary observatories covering an aera, say, 100 to 1000 m² distributed all over the watershed.

Due to logistic problems and uninhabited terrains which remain uncovered by manned stations, advantage should be taken of the following approaches:

(a) Installing telemetery system, connecting automatic recording instruments installed at the site with the main and subsidiary manned stations. Calibrated poles may also be read by powerful binocular from distances of few 100 metre.

(b) Installation of data collection platform operating through satellite. Periodic reconnaissance or survey with portable equipment.

- *Monitoring of snowline altitude variations can be made by*

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

(b) mapping of sattelite imageries on cloud-free days;

(c) survey by air.

7.4 Technological Advances & Gaps in Knowledge

Many of the major advances in glaciology during the past few decades have followed the application of new technology for viewing and measuring various characteristics of snow and ice. Microscopes to study ice crystals, radars to probe the internal structure of large ice masses, mass spectrometers to analyse the atomic composition of ice cores, and satellite sensors to measure the global distribution of ice are some of the tools readily adapted by glaciologists. Today, new tools include microcomputers for automatic data processing and numerical modeling, sensitive instruments for ice analysis, and satellite sensors for large-scale ice observations. In the future, continued advances in key technologies will help guide the evolution of understanding various aspects of glaciology and the interactions within the ice-ocean-land-atmosphere system.

Some major advances in glaciology with the technological developments (Zwally, 1987) during last 3 to 4 decades are given in Table 9.

TABLE 9 : ADVANCES IN GLACIOLOGY WITH TECHNOLOGICAL DEVELOPMENT

	Major advances in Glaciology	Technological Developments
1.	Ice-sheet thickness/ topography/basal conditions.	Seismometry, Radio Echo-sounding, Satellite-Radar Altimetry.
2.	Glacial History.	Ice-core Drilling, Isotope Spectrometry, Unstable- Isotope Dating, Contaminant Analysis
3.	Sea-Ice Motion/Forcing.	Automatic Data Buoys, Satellite Imagery.
4.	Global Sea-Ice Extent and Open Water.	Satellite Passive Microwave Imaging.
5.	Ice-sheet Velocities	Satellite Geodetic Positioning.
6.	Ice-Dynamics Modelling	High-Speed Computers
7.	Ice-Margin Mapping	Photography.

Gaps in knowledge can be filled using satellite data (Kotliakov & Krenke, 1982).

i. position of snowline and the snow-melting front on the basis of visible and near-infrared images;

ii. operational use of active and passive microwave methods for estimation of water equivalent of snowcover;

iii. ice topography;

iv. surface velocity of ice.

It is also necessary to organize the network of ground surveys of accumulation, ablation, cloudiness and air-temperature over the ice covers, specially devised on a global scale. Emperical generalisations of the relations of these indices to the morphology of ice sheets are also desirable. It is expedient to establish the global network of boreholes in ice with selection of core for the reconstruction of the past-glacial climates.

Radiation measurements are needed in different wavelength bands for determining brightness, temperature, albedo and roughness of glacier surfaces and snow cover.

Let us recall that pure ice is very simple in physical and chemical terms and it is an ideal material for studying a wide range of problems in material science but the natural ice needs in-situ measurements. Planning based on the results of basic and applied research will be helpful for sustainable development of natural resources of the region.

CONCLUDING REMARKS

The interdisciplinary science of Himalayan Glaciology is difficult but more exciting and challenging as compared to Arctic or Antarctic Glaciology or the Glaciology of the other mountain glaciers as we have a combination of polar, temperate and tropical type of glacier systems. The complexity is due to ultra high altitude environment criss-cross mountains and the lower latitudes. This should be taken as a pointer to the need for greater scientific inputs to study these apex systems as available knowledge from other parts of the world cannot be really satisfactorily used for any quantitative estimations. Our high altitude environment provides large glaciers which rival those of polar regions and these glaicers being the renewable natural reservoirs, at the apex have contributed a great deal to the development of the Indo-Gangetic plains. The Himalayan mountains provide a unique opportunity for making open laboratory experiments under a variety of climates for scientific research and understanding of the natural environment.

As the Himalayan terrain involves many countries, international cooperation for the challenging task will be more fruitful. Developing appropriate institutional infrastructure to address the problems on a continual basis can be very rewarding indeed. Let us give the Himalayas the scientific respect they have deserved all this time.

We have to study in greater detail the land-atmospheric interactions for the studies of climate dynamics, high altitude lakes, meltwater contributions to streamflows, rates of erosion and siltation, rate of uplift and associted seismicity, floral and faunal distribution with their productivity through extensive and intensive observations. Studies of Himalayan glaciology and the glacier modelling are also of great interest for understanding their influence on the monsoon circulation on various temporal scales. These studies will help us to evolve appropriate set of technologies for regeneration of this high altitude Himalayan environment which could preserve and enhance the pristine beauty concurrently satisfying the needs of various sections of society, preventing desertification of the serne environment (due to overexploitation of its natural resources). All this is possible if interested research groups covering different disciplines are established in Himalayan Universities and supported by the Interdepartmental National Committee for Himalayan Glaciology. Infrastructure support may be provided by other R&D Institutions and Organisations as necessary. The whole effort deserves scientific and Institutional support

i. to look for practical answers to problems related to snow and ice, disaster prevention (outburst of glacier dammed lakes, glacier surges and snow and ice avalanches) hydropower production, planning recreational facilities, etc.;

ii) to develop appropriate methodologies for forecasting melt contributions to streamflows to suitably deal with the flood drought syndrome plaguing the national economy.

iii) to assess the impact of climatic change or shift on the apex environment and the associated river systems

To unravel the climate-glacier puzzle, several decades of observations are necessary on the glaciated environment.

From time to time, concerns have been expreessed to have a close watch on Himalayan ecosystems and particularly water resources systems at the apex of which are situated snow and ice fields, but no integrated system exists even today for national documentation of information on the subject. There is need to have a high level standing agency which overviews the work of multidisciplinary groups and provide adequate resources and a forum to monitor the physical, chemical and biological changes connected with the preservation and development of the great environmental asset of nature to our society.

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ANNEXURE - I

GLOSSARY

ABLATION

All processes by which snow, ice or water in any form are lost from a glacier or snow cover.

ABLATION AREA

That part of a glacier's surface over which ablation (wastage) exceeds accumulation each year.

ACCUMULATION

All processes by which snow, ice or water in any form is added to a glacier or snow cover.

ALBEDO

That fraction of incident light reflected in all directions from a surface.

AVALANCHE

Snow avalanche is the fall by gravity of a mass of snow down a mountain slope. It is effected by the internal cohesion of the snow, the thickness and density of the snow layer, the character of the underlying material and the slope of the terrain.

BASAL GLIDING

Yielding of a crystal by interatomic slippage on a plane with basal crystallographic orientation.

BASAL SLIP

Slippage of a glacier over its bed.

BERGSCHRUND

The crevasse which occurs at the head of a cirque or valley glacier which separate the moving glacier ice from the rock wall and the ice apron attached to it.

CALFING

The breaking away of a mass of ice from a floating glacier, ice front or iceberg.

CIRQUE GLACIER

A glacier which occupies a separate rounded recess which it has formed on a mountain side.

COL

Open, U-shape pass across a high, narrow mountain ridge created by glacial erosion.

COMPRESSING FLOW

Created by longitudinal compression in any reach of a glacier experiencing decreasing flow velocity; causes surfaceward movement of ice and an increase in thickness.

CONTINENTAL ICE SHEET

Sheet of ice of continental proportions, largely burying the underlying landscape and flowing outward in all directions.

CONVECTION

Transfer of heat within fluids by currents resulting from differences in density caused bydifferential temperature.

CREEP

Slow, essentially continuous, nonrecoverable deformation (movement) sustained by soils, rocks, and minerals (ice).

CREVASSE

A fissure formed in a glacier. Crevasses are often hidden by snow bridges.

CRUST

A hard snow surface lying upon a soft layer. It can be formed by sun, rain or wind.

CRYSTAL

Regular, solid, geometrical form bounded by plane surfaces, expressing an internal ordered arrangement of atoms. Aggregates of crystals may have irregular forms.

DEAD ICE

Any part of a glacier which has ceased to flow. Dead ice is mostly covered with moraine.

DECLINATION

Diference, at any location, between the bearings to the magnetic pole and the geographic pole of Earth.

DRUMLIN

Low, streamlined ridge of glacial drift (rock detritus carried and deposited in any mode by glacier) shaped by an overriding glacier.

EQUILIBRIUM LINE (of firn and G; snow line)

The line or zone on a glacier where a year's ablation balances a year's accumulation. It is a determined at the end of the ablation season.

ERRATIC

Rock fragment, typically large, transported and deposited by a glacier.

ESKER

Long, low, narrow, commonly sinuous ridge of glaciofluvial material desposited in a subglacial ice tunnel or an ice-walled channel.

EXTENDING FLOW

Created by extension within a glacier where flow is accelerating; causes thinning.

FIRN

Old snow which has transformed into a dense material.

FIRN LINE (of Equilibrium and snow line)

The line or zone on a glacier that separates bare ice from snow at the end of the ablation season.

FLOE

A piece of floating ice other than glacier ice.

FOLIATION

Crude mineralogical or textural banding formed in rocks, primarily by solid-state metamorphism.

HOLOCENE EPOCH

Past ten thousand years; succeeds the Pleistocene (approximately 1.6 million years of earth history essentially equivalent to the last glacier ice age).

FRAZIL ICE

Find spicules or plates of ice in suspension in water.

FROST SMOKE

Fog-like clouds, due to the contact of cold air with relatively warm water, which appear over newly formed leads, or leeward of the ice edge, and which may persist while new ice is forming.

GLACIER

A mass of snow and ice continunously moving from higher to lower ground.

GLACIER FLOOD

A sudden outburst of water released by a glacier.

GLACIER POT-HOLE

A deep and more or less vertical hole in a glacier. Glacier pot-holes drain away surface melt water.

HAIL

Precipitation of small balls or pieces of ice with diameter ranging from 5 to 50 mm or more.

HOARFROST

A deposit of ice having a crystalline appearance, generally assuming the form of scales, needles, feathers or fans; produced in a manner similar to dew (i.e. by condensation of water vapour from the air), but at a temperature below O°C.

ICE APRON

A thin mass of snow and ice adhering to a mountain side.

ICE JAM

An accumulation of broken river or sea ice caught in a narrow channel.

ICE SHEET

A mass of ice and snow of considerable thickness and large area. Ice sheets may be resting on rock (Island Ice sheet) or floating (Ice shelf).

ICICLE

Hanging spike of clear ice formed by the freezing of dripping water.

INSOLATION

Radiated energy received from the sun.

KAME

Steep-sided a rock or ridge of glaciofluvial debris deposited in contact with glacier ice.

KETTLE HOLE

Normally bowl-shaped, topographically closed depression within glacial drift formed by melting of a large chunk of partly or completely buried glacier ice, usually filled with water.

KINEMATIC WAVE

Wavelike perturbation of a glacier's steady-state flow that moves outward at a velocity several times normal.

MORAINE

Ridges or deposits of rock debris transported by a glacie. Common forms are: ground moraine, formed under a glacier; lateral moraine, along the sides; medial moraine down the centre; and end moraine; deposited at the foot. Moraines are left after a glacier has receded, providing evidence of its former extent.

MOULIN

Roughly cylinderical, nearly vertical hole upto 30m in a glacier's surface.

NET BUDGET

The difference between accumulation and ablation; usually expressed in terms of water equivalent per unit area.

NEVE

French term for old granular snow; called firn in German.

NEW SNOW

A recent snow deposit in which the original form of the ice crystals can be recognised.

NUNATAK

A rocky crag or small mountain projecting from and surrounded by a glacier or ice sheet.

OGIVE

Band or wave on the surface of a valley glacier stretching from side to side and arched in the direction of flow.

OLD SNOW

Deposited snow whose transformation into firn is so far advanced that the original form of the ice crystals can no longer be recognised.

OUTLET GLACIER

A valley glacier which drains an inland ice sheet or icecap and flows through a gap in peripheral mountains.

PERENNAILLY FROZEN GROUND

Continually below O°C, year after year. (Equivalent: Permafrost).

PERFECTLY PLASTIC SUBSURFACE

Shows no deformation under increasing shear stress up to a point, after which it deforms continuously without rupture or further increase in stress.

PERIGLACIAL

Cold, rigorous environment characterizing the area peripheral to a large Pleistocene glacier, and the processes and products found there.

PIEMONT GLACIER

The lobe shaped, expanded, terminal part of a valley glacier spread out over broad lowlands at the base of mountains.

PLUCKING

Glacial erosive process whereby sizable blocks of rock are loosened, picked up, and carried away by glaciers (Synonym: Quarrying.)

PRESSURE MELTING

Melting of ice where pressure is great enough to lower its melting point below the ambient temperature.

PROGLACIAL

Area lying adjacent to and usually in front of a glacier.

PUDDLE

An accumulation of melt water on ice surface, mainly due to melting snow.

RAFTING

Pressure process by which one floe (a piece of loating ice) overrides the other.

RIME

A deposit of ice composed on grains more or less separated by trapped air, sometimes adorned with crystalline branches, produced by the rapid freeezing of supercooled and very small droplets.

RIVER ICE

Floating ice in rivers.

SLEET

Precipitation of snows and rains together, or of snow melting as it falls.

SLUSH

Snow which is saturated and mixed with water; found on land or ice surface or as a viscous floating mass in water after snowfall.

SNOW

Precipitation of ice crystals, most of which are branched (sometimes star shaped). The branched crystals are sometimes mixed with unbranched crystals. At temperatures higher than about -5°C the crystals are generally agglomerated into snowflakes.

SNOWLINE

A line or zone on land that separates areas in which snow remains throughout the year. The altitude of the snowline is controlled by temperature and the amount of snowfall.

STRIAE (STRIATIONS)

Linear, finely cut parallel scratches inscribed on a rock surface by debris carried in basal ice of a moving glacier.

SURGE

Relatively short-lived episode of greatly accelerated flow within a glacier.

VALLEY GLACIER

A glacier which flows down a valley.

VARVE

Glaciolacustrine sedimentary copuplet of contrasting summer and winter laid material, representing one year of deposition.

WHALEBACK

Smooth, glacially sculptured bedrock knob of modest size resembling the back of a sounding whale.

ANNEXURE - II

PRINCIPAL GLACIERS IN HIMALAYA

1.	Rakhiot	Punjab Himalaya
2.	Kolhai	
3.	Neh-Nar	
4.	Sarbal	
5.	Kangriz	
6.	Brahma	
7.	Drung Drung	
8.	Mulkila Group	
9.	Barashigri	
10.	Glacier in Dibi Bokri Area	
11.	Gara	
12.	Gorgarang	
13.	Gangotri	Garhwal Himalaya
14.	Santopath	
15.	Kedarnath	
16.	Milam	
17.	Pindari	
18.	Shankulpa	
19.	Poting	
20.	Yaling	Nepal Himalaya
21.	Chong Kumdan	
22.	Rundun	
23.	Glaciers adjoining to Dhaulagiri & Annapurna Peaks	
24.	Kang Shung	
25.	Rupal	
26.	Khumbu	
27.	Glacier adjoining Makalu	
28.	Zemu	
29.	Glacier adjoining Kanchenjunga peak	Assam Himalaya
30.	Sanlung	
31.	Glaciers adjoining Gyara Pari Peak	

Source : Survey of India - Internal Report, 1985

ANNEXURE - III

POTENTIAL HYDROPOWER ON HIMALAYAN RIVER SYSTEMS*

NAME OF THE RIVER SYSTEM	POTENTIAL AT 60% LOAD FACTOR (MW)
INDUS	19,998
GANGA**	10,715
BRAHMAPUTRA	34,920

*Source : Hydropower Potential of India, Central Electricity Authority, New Delhi. Dec., 1988 Printed by National Hydroelectric Power Corporation Ltd.

** The power potential would be considerably enhanced if collaborative power projects are implemented with the cooperation of Nepal and Bhutan.

ANNEXURE - IV

GLOBAL WATER RESOURCES

A - WORLD WATER INVENTORY

Residence	Volume (10^6 Km^3)	Per cent of total (Approximate)
World Ocean	1,350	97.6
Rivers, Lakes and Ground Water	8.6	0.6
Glaciers (Water Equivalent)	24	1.7
Atmosphere	.013	Trace
Total	1,382.613	99.9

Source : Flint, R.F., 'Glacial and Quaternary Geology, John Wiley & Sons, Inc. NY, 1971 pp.892.

B - GLOBAL ANNUAL SNOWCOVER

Snow Cover		Area 10^6 Km^2	Accumulation Kg/m^2	Mass 10^9 tons/km^3 of water
A)	**NORTHERN HEMISPHERE**			
i)	Permanent snow on glaciers.	2	250	500
ii)	Seasonal snow on land	59	140	8,300
iii)	On pack ice	9	100	900
iv)	On seasonal sea ice	9	120	1,100
B)	**SOUTHERN HEMISPHERE**			
i)	Permanent snow on glaciers	14	160	2,200
ii)	Seasonal snow on land	2	150	300
iii)	On pack ice	5	180	900
iv)	On seasonal sea ice	15	200	3,000

Source : Shumsky, P.A., Krenke, A.N. & Zotikov, I.A. (1964): Ice and its Changes in: Geophysik of Earth, Vol.II, Washington.

C - GLOBAL GLACIERIZATION

	Glacierization	Area, 10^6 Km^2		Volume	
		Accumulation	Ablation	Total	10^6 Km^3
A)	**NORTHERN HEMISPHERE**				
i)	Continental ice sheets	1.1	0.6	1.7	2.7
ii)	Ice sheets on islands	0.2	0.15	0.35	0.2
iii)	Mountain Glaciers	0.1	0.1	0.2	0.03
B)	**SOUTHERN HEMISPHERE**				
i)	Continental ice sheets	13.8	0.1	13.9	28.0
ii)	Mountain Glaciers	0.02	0.01	0.03	0.01

Source : 1) Shumsky, P.A., Krenke, A.N. & Zotikov, I.A. (1964): Ice and its Changes in: Geophysik of Earth, Vol.II, Washington.

2) ICEX (1979). Ice and Climate Experiment, Greenbelt, Maryland, 1979.

AUTHOR'S BIOGRAPHICAL SKETCH

The author has more than 32 years field experience in a variety of scientific disciplines. Starting as lecturer after his M.Sc. Physics in 1959 from Lucknow, he joined ONGC from where he worked in various parts of the country for petroleum covering the states of Orissa, West Bengal, Gujarat, Rajasthan, Tamil Nadu and U.P. In 1964, he moved to CWPRS, Pune for research work in the field of isotopes for civil engineering problems. On the work, he was awarded Ph.D. by Pune University in 1969. CBIP awarded him a gold medal for a review on utilisation of isotopes. He won a Global Post-doctoral Fellowship towork on snow and glacier hydrology in Norway. He visited several Himalayan glaciers feeding Sutlej, Chenab and Ganga rivers during the period 1972-88. From June, 1972 he worked at NRL, IARI under UNDP Project on Nuclear Research in Agriculture contributing significantly to the efficient use of water.

On his return from foreign assignment in Libya, he joined Department of Science and Technology and evolved an All India Coordinated Programme on Himalayan Glaciology, with which he continues to be associated. Presently, he is working as Director for development of agrometeorological services at National Centre for Medium Range Weather Forecasting (NCMRWF).