# WATER YIELD FROM SNOW AND GLACIERS

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## INTRODUCTION

About 80% of the world's fresh water resources are stored in the form of snow and ice and cover about 10% of the total land mass of the earth (14.9 million km²). Most of the permanent snow and ice mass is stored in the Polar regions and nearly 3% of this is distributed over mountains in the various continents. This small amount, however, is of great importance because of its proximity to the populated areas. Glaciers are found on every continent except Australia. Extensive mountain glaciation is found in Alaska, Iceland, Norway, Russian Arctic Island, the Alps, the southern Andes, the Karakoram and Himalayan mountain ranges. Most of the glaciation is concentrated in the northern Hemisphere with exception of Antarctica. Out of all mountain glaciers, Central Asian mountains contain about 50% of the glaciers, a large portion of which drains into the land mass of Indian sub-continent. The principal glacier fed river systems of Himalaya are shown in Table 1 from which it would be evident that snow and glaciers have significant potential of water resources in India. Figure 1 shows the global seasonal snowcover.

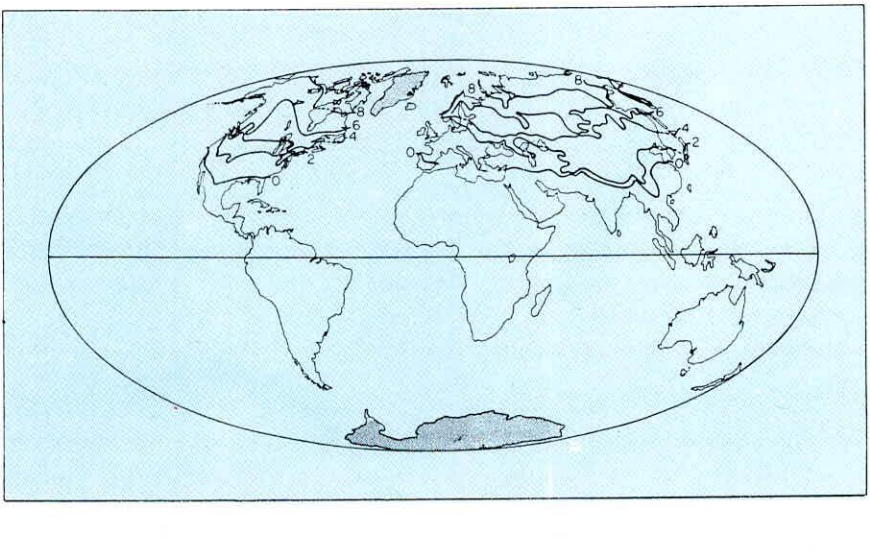

**Fig. 1. Seasonal snowcover. The numbered lines represent the duration of the snowcover in months. The major ice sheets are shaded. (Rikhter, 1960)**

**Table 1 : Principal snow and glacier fed river systems of Himalayas**

| No. | Name of River | Major River System | Mountain area ($km^2$) | Glacier area ($km^2$) | %age glaciation |
|---|---|---|---|---|---|
| 1. | Indus | | 268,842 | 8,790 | 3.3 |
| 2. | Jhelum | | 33,670 | 170 | 5.0 |
| 3. | Chenab | Indus | 27,195 | 2,944 | 10.0 |
| 4. | Ravi | | 8,029 | 206 | 2.5 |
| 5. | Satluj | | 47,915 | 1,295 | 2.7 |
| 6. | Beas | | 14,506 | 638 | 4.4 |
| 7. | Yamuna | | 11,655 | 125 | 1.1 |
| 8. | Ganga | | 23,051 | 2,312 | 10.0 |
| 9. | Ramganga | Ganga | 6,738 | 3 | 0.04 |
| 10. | Kali | | 16,317 | 997 | 6.0 |
| 11. | Karnali | | 53,354 | 1,543 | 2.9 |
| 12. | Gandak | | 37,814 | 1,845 | 4.9 |
| 13. | Kosi | | 61,901 | 1,318 | 2.1 |
| 14. | Tista | | 12,432 | 495 | 4.0 |
| 15. | Raidak | Brahamputra | 26,418 | 195 | 0.7 |
| 16. | Manas | | 31,080 | 528 | 1.7 |
| 17. | Subansiri | | 18,130 | 725 | 4.0 |
| 18. | Brahamputra | | 256,928 | 1,080 | 0.4 |
| 19. | Digbang | | 12,950 | 90 | 0.7 |
| 20. | Luhit | | 20,720 | 425 | 2.0 |
| | TOTAL | | 1,001,294 | 25,724 | 2.6 |

In addition, a huge area of the earth is covered by seasonal snow which melts away during snow melt season and feeds the rivers during the lean season when water from other sources is negligible. The water drained out from the snow and glaciers due to their melting during summer is a source of fresh water and generation of hydro-electric power in several countries. For example, the economy of Norway, and Iceland is dependent on the amount of water produced from the snow and glaciers in that region. The changes in the glaciers also reflect the changes in the climatic processes of the region. By virtue of snow and glaciers, all the rivers originating from the Himalayas are perennial in nature. Thus seasonal snow and glaciers are of importance in the local, regional and continental water resources.

## THE HIMALAYAS

The Himalayan mountains are the world's largest and highest mountains where the normal range of human operations is not possible. It may be pointed out that 35% of the geographical area in India is mountainous and 58% of this is accounted for by the mighty Himalayas. The role of this control structure in the climatology and water resources is well pronounced in the Indian sub-continent. The major river systems of the Indus, Ganga and Brahmaputra originate from its vast snow fields.

The Himalayas are an extensive mountain system of 2400 km from Nanga Parbat (8126 m) in the west to Namcha Barua (7756 m) in the east in the shape of a convex with its convexity toward the south. The Himalayas may further be subdivided laterally into western, central and eastern Himalayas. The western Himalayas extend from Nanga Parbat to Nanda Devi and is the origin of Indus and Ganga river. The central Himalayas stretch from Ghaghra and Gandak to Kosi river system and limited to Nepal Himalayas, whereas the eastern Himalayas range from east of Kosi to Namcha Barua in bend of Brahmaputra river (Figure 2).

As indicated above, the Himalayas are not a single chain of mountains. They consist of three west to east running parallel ranges and

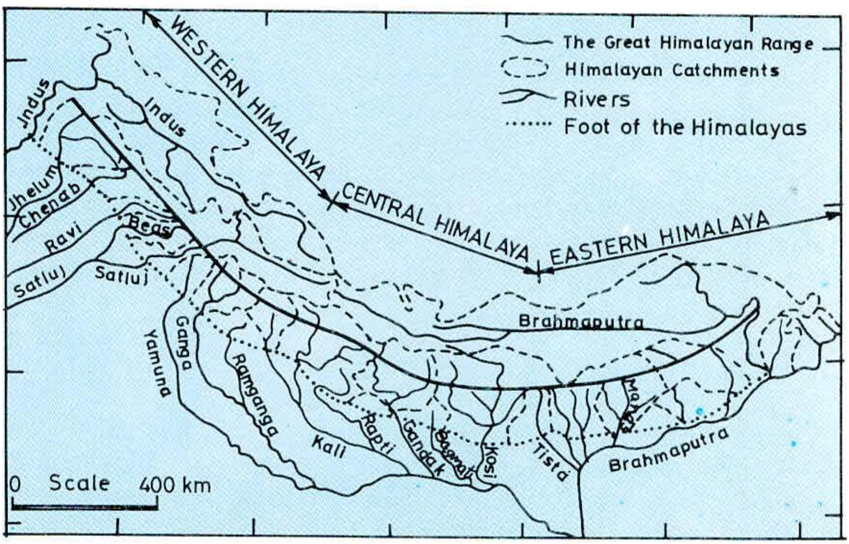


Fig. 2 Different sections of Himalayas and catchments of the Himalayan rivers.

between these ranges there are numerous narrow valleys. Three parallel ranges or geographical zones namely outer Himalayas, middle Himalayas and greater Himalayas are described below.

### (i) Outer Himalayas

This is the southern most range of Himalayas and is known as Siwalik ranges also. Their average height varies from 900 to 1200 m asl and average width varies from 10 to 50 km. Attaining an altitude of about 600m they end abruptly and follow successive narrow parallel ridges. The elevation of these outer hills rarely exceeds 1200 m.

### (ii) Middle Himalayas

The ranges representing this part of Himalayas consist of higher mountains. These are a series of broken mountain ranges whose mean elevation varies from 2000 m to 3300 m asl. The width varies from 60 to 80 km. These ranges have different names in the different sections of the Himalayas such as Lesser Himalayas or Pir-Panjal ranges in the western Himalayas. The middle Himalaya lies between the outer Himalaya and the perpetual snow covered ranges of greater Himalaya. It is characterized by deeply cut valleys. The ridges extending in irregular direction appear to branch again and again.

### (iii) Greater Himalayas

This is the most northern range of the Himalayas. It is lofty, rugged chain reaching high above the perpetual snowline. The average height of this range is about 6000 m asl. In this great Himalayan range as many as 13 peaks exceed 6000 m elevation. A still large number of peaks range from 4500 m to 6000 m. Beyond the main ranges of Himalaya, there is a continual series of somewhat lower Trans-Himalayan zone (average altitude varying between 5000 m and 6000 m) adjoining the Tibetan plateau.

## HIMALAYAN CLIMATE

The great contrast in the geographical relief results in a variety of climates in the Himalayas. Such regions are characterized by climatic differences over short horizontal distances. Principal factors producing such differences are those of altitude, local relief and mountain barrier. The main reason for systematic dependence of climate on physiography is its relation to elevation. However, the actual distribution of these factors is largely determined by the patterns of landscape and other physiographical contrasts in slopes, valleys etc which are responsible for differences in climate over short distances.

The important factors which control the weather and climate in the Himalayas are altitude and aspect. Largely due to variations in altitude, the climate varies from hot and moist tropical climate in lower valleys, to cool temperate climate at about 2000 m and tends toward polar as the altitude increases beyond 2000 m. Altitude controls not only temperature but rainfall also. The second factor controlling the climate is aspect. Usually the south facing slopes are more sunny and also get more rain. Further, in each individual range the snowline is higher on southern slopes as they have more sunshine. The snow line in the eastern Himalayas is higher than in the western Himalayas.

## PRECIPITATION CHARACTERISTICS

Knowledge of precipitation distribution during individual months, seasons and the year is of vital importance both for planning water resources projects and agricultural operation in a given basin/region. Depending upon broad climatic conditions prevailing over the Himalayas, the following four seasons are well marked in the Himalayan region.

(i) Winter season (December-March)
(ii) Pre-monsoon season (April-June)
(iii) Monsoon season (July-September)
(iv) Post-monsoon (October-November)

The source of precipitation and its distribution in each of the season is as follows.

### Winter Season

The precipitation during this season is caused by extratropical weather system of mid latitude region originating from Caspian sea and moving eastward. They approach India from the west through Iran, Afghanistan and Pakistan. With the setting of the winter season these disturbances have the tendency to move along lower latitudes. Normally, these disturbances remain at high latitudes and do not influence the Himalayas. But, as the season advances they come lower and lower and by the end of December they cover a large part of Himalayas. They recede to their original position beyond the Himalayan mountains after winters.

The precipitation during this season is generally in the form of snow in the greater Himalayas, snow and rain in the middle Himalayas, and only rain over the outer Himalayas and the adjoining north Indian plains. Precipitation occurs at intervals throughout the winter season. It is found that average frequency of occurrence of these extratropical disturbances is about 3 to 5 each month and reduces as the season advances.

The higher precipitation in the western Himalayas during these months is the combined effect of the nearly east-west configuration of the Himalayas and eastward movement of weather systems in winter. The precipitation associated with these weather systems decreases considerably as they move eastwards along the Himalayas because of increasing distance from the source of moisture.

## Pre-monsoon Season

Generally this season lasts for about a period of 3 months from April to June and is considered as transit period between winter and southwest monsoon. Light to moderate rain is caused by convective storms. Convective activity increases as the season advances because of increase in temperature over the Himalayan region.

## Monsoon Season

Normally precipitation over the Himalayas is caused by the moist air currents from Bay of Bengal in this season. Sometimes, in association with certain weather situations both branches of monsoon (i.e., the Bay of Bengal and Arabian sea) arrive simultaneously in this region heralding the onset of monsoon. These currents after striking the Burma and eastern Himalayas are deflected westwards and travel along the Himalayas. Rainfall decreases westward because of increasing distance from the source of moisture i.e. Bay of Bengal or Arabian Sea, which results in less amount of moisture content in the air currents. Consequently lesser precipitation is observed as one moves further and further to the west. This is the season of abundant rain and Himalayan rivers are generally flooded. Snow and glaciers at very high altitudes continue melting during this season. The monsoon normally starts withdrawing from this region towards the end of September. While the monsoon currents give copious rainfall over the Indian plains, after they cross the Himalayan ranges and move over trans-Himalayan regions they become dry as most of the moisture they initially carried is precipitated during their passage over the plains and mountain ranges of the Himalayas.

## Post Monsoon

During this season clear autumn weather sets in and there is generally little rainfall. This is the driest season in the entire Himalaya.

The precipitation during different seasons as a percentage of annual precipitation in the different sections of Himalayas is shown in Table 2 (Gulati, 1972).

## SEASONAL SNOW COVER

The snow accumulates during the winter season in the upper part of most of the rivers originating from the Himalayas. Maximum extent of snow covered area is observed in the month of March. Catchments in the western part of the Himalayas get more snowfall because they are in direct line of the western disturbances than the eastern parts. Especially during February and March, the western Himalayas gets maximum snowfall. Snow cover area starts reducing with the onset of spring and reaches to its minimum by the end of September/ October. The snow cover in the Himalayas is controlled by the terrain and climatic conditions of the region.

**Table 2: Percentage of seasonal precipitation in different Himalayan sections.**

| Himalaya Section | Snow Accumulation season | Snow melt season | Monsoon season | Ground water |
|---|---|---|---|---|
| Kashmir Himalaya | 22.1 | 22.0 | 53.6 | 2.3 |
| Punjab Himalaya | 11.1 | 8.1 | 78.4 | 1.6 |
| Garhwal Himalaya | 6.0 | 3.6 | 87.8 | 2.6 |
| Nepal Himalaya (Western & Central) | 3.9 | 2.9 | 88.0 | 5.2 |
| Nepal Himalaya (Eastern) | 2.9 | 6.8 | 85.0 | 5.3 |
| Sikkim Himalaya | 2.0 | 16.5 | 74.6 | 6.9 |
| Assam Himalaya | 2.4 | 25.7 | 65.8 | 6.1 |

The snow covered area derived from satellite data is primarily useful in snow melt runoff modelling. To assess the variability of snow cover area, a long-term continuous monitoring of snow cover is required. The snowbound area in the Himalaya in winter including permanent snow is reported to be 10,00,000 km$^2$ considering area between 70$^0$ E and 40$^0$ N (Dhanju, 1983). Changes in the seasonal snow cover area plays an important role in the weather and water resources of India and neighbouring countries. Systematic studies on precipitation in the form of snow and seasonal snow cover are of recent origin in India. Basinwise variability of distribution of snow cover area in the catchments of Himalayan rivers has to be studied and used for hydrological studies.

Those parts of the earth where the rate of snowfall is greater than melting of snow and low temperatures along with suitable topographic and climatic factors exist, are ideal for snow to deposit and survive i.e. for glacier formation. This is the reason that glaciers are found in the Himalayan region above about 4000 m altitude. Snow is transformed into glacier ice because of metamorphism of the snowpack. The pressure induced by weight of the overlying snow causes the transformation from snow to ice. The density in different weather conditions and various stages are given in Table 3 The density of glacier ice ranges between 0.80-0.90 gm/cc. The time taken for conversion of snow into ice varies with temperature of the region.

## MELTING OF SNOW AND GLACIERS

The timing and amount of melt water produced from mountain glaciers is different from that derived from snowpacks on land. The major contribution from the seasonal snow reaches the streams between March and June (before monsoon). The glaciers starts melting when all the snow accumulated in the last season is melted. The melt water from the snow and glaciers is delayed before joining a stream or ground water reservoir. This delay is more prominent in the glaciers. Although insolation reaches a peak in June in the northern Hemisphere, the average albedo of snow covered glacier surface at this time is relatively higher causing only low or moderate melt rate. In July and August, insolation is slightly reduced but the mean albedo of the glacier surface drops markedly as old dirty ice gets exposed, and the rate of melt is found to be higher than in June. A year of heavy snow accumulation results in a layer of high albedo snow persisting longer into the summer season and curtailing melt. A dry winter or a hot summer results in increased melt. Thus production of melt water from glaciers tends to compensate for unusually wet or dry, or hot or cold years thereby naturally regulating the streamflow.

### Water Storage and Drainage Characteristics

During the melt season the glacier acts like a reservoir which is drained continuously by the streams emerging at its terminus and refilled daily by melt water. The movement of melt water arises from accumulation and ablation area. While in transit at different velocities through the various hydrological pathways of the internal drainage system, liquid water is effectively stored in several locations within a glacier such as snow and firn, pools on the ice surfaces, crevasses, englacial pockets, subglacial cavities, the moulins-conduits network and basal moraines. Water storage in glaciers fluctuates over period of several days with hydrometeorological conditions, resulting in melt stream discharge having diurnal saw-toothed peaks superimposed on a background flow, the volume of which varies more slowly. Only a portion of melt water produced each day is drained out from the snout on the same day. Runoff of remainder is delayed until succeeding days, adding to later daily melt contribution. The runoff delay from the ablation area of the Chhota Shigri glacier in the Himachal Pradesh has been found to be between 2-3 hours (Singh, 1991). The presence of glaciers in a basin also delays the time of maximum runoff because of their melt water storage characteristics. Figure 3 shows accumulation zone of Chotta Shigri glacier (H.P.) where stratigraphic study was carried out by National Institute of Hydrology.

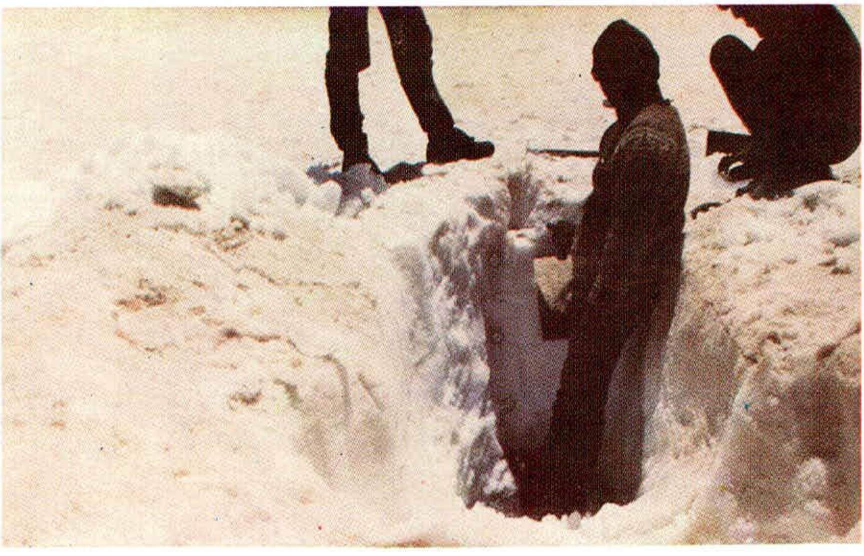

**Fig. 3. A view of accumulation zone of Chhota Shigri glacier and snow pit for stratigraphic studies**

The discharge in the melt water stream is generally found to be low in the morning and increases towards the late afternoon and early evening. The melting and pattern of melt are primarily controlled by incoming solar radiation and associated air temperature variations, as well as the dominant streamflow generation processes. The diurnal fluctuation is virtually non-existent in winter and begins to appear in early summer. Its amplitude tends to increase towards late summer when glacier ablates with its highest intensity. The diurnal variation is progressively increased through the melt season. This is the result of an increased radiation energy input due to lower albedo of ice as compared to snow. As the glacier surface becomes snow free, as well as the progressive development of the glacier drainage system through summer, the time of peak flow shifts from late in the evening in May to shortly after solar noon in September due to the increased hydrological responsiveness of the glacier. A view of the Chhota Shigri glacier melt stream and gauging site established by National Institute of Hydrology is shown in Fig. 4.

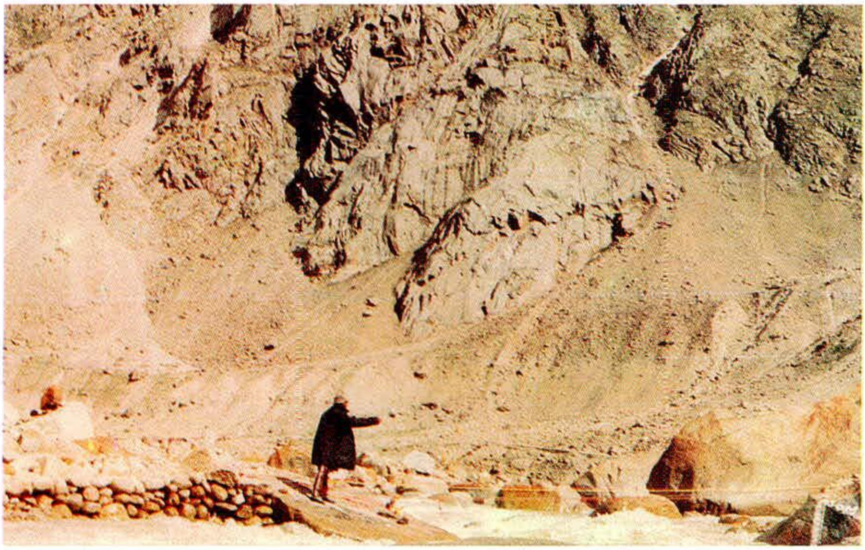

**Fig. 4. Chhota Shigri glacier melt stream and gauging site established by National Institute of Hydrology for discharge observations.**

## CONTRIBUTION OF SNOW AND GLACIERS

Basic requirements for proper management of high-mountain water resources include knowledge of amount and location of water stored in frozen form, the pattern of water release by melting and how the pattern of release depends on short-term and long-term climatic changes. The assessment of the yield from snow and glacier into various Himalayan rivers is the most important part of hydrology. This figure can be used in planning and management of water resources projects in the Himalayas. Estimates are worked out only for few rivers. It is reported that for Ganga river at Devprayag the contribution from the snow and glaciers in the annual flows is about 28%, whereas that for Chenab river at Akhnoor is about 50%. It shows that snow and ice have vast potential for water resources development in India. Such studies are required for all the Himalayan rivers.

In view of ever increasing demand of water for irrigation, hydro-electric power generation, domestic and industrial use, and role of Himalayan rivers in satisfying the requirement, systematic studies to understand the snow and glacier melt runoff processes and their storage and drainage characteristics are necessary. Simultaneously, network for collecting hydrometeorological data at higher altitudes in the Himalayan region is to be strengthened so that seasonal input to the vast snow and glaciers reservoirs can be estimated and water yield studies for all the Himalayan rivers can be carried out. The temporal distribution of this yield would be of much use for water resources planning and management.

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