Himalayan glaciers

Jagdish Bahadur

Vigyan Prasar, New Delhi, India

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vigyan@hub.nic.in

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ABSTRACT

Himalayan snow and glaciers are apex natural water resource reservoirs and release large quantity of freshwater year round. Their ultrahigh altitudes attract moisture from Indian, Atlantic, Pacific and Arctic oceans. The uplift of the mountains have given birth to Indian Monsoon. Their rugged topographic features modify weather systems at all scales of space and time. Meltwater releases moderate drought and flood conditions and coldwater discharges to Indian ocean modifies its circulations. Himalayan mountains are the youngest and most active and coupled atmosphere - snow - land - ocean systems. As the mountain system is bestowed with all microclimates (from dry-cold to wet-hot), it is one of the mega biodiversity region for flora and fauna, supporting a huge human population. This sensitive and fragile region needs continuous monitoring to understand the physical processes for effective utilisation of its natural resources and timely corrective measures to reduce the occurrence of natural disasters
for harmonious environmental conditions.

INTRODUCTION

Between 10-15 million years ago, the sub-continent of India riding its own earth plate collided with the rest of the Asian landmass. The pressure squeezed the earth crust, forcing it to pop up further inland. Thus, Himalayas were formed by crumpling of the earth's crust. The uplift of the Himalayas was a gradual process over a long period. During this time, the Tibetan Plateau was also pushed up by 2000 to 3000 meters. As the elevation of the mountains reached above the permanent snowline (the altitude where the snow falls round the year) it was transformed as the house of so-called 'eternal snow and ice' forming the Himalayan glaciers. For over 2 million years, these glaciers have sculpted the Himalayan landscape and influenced the course of human history. As a result of Himalayan uplift, the present monsoon conditions were created. We shall now briefly discuss the formation of a glacier (please see the box for general information about glaciers and their behavior).

Freshly fallen snow is a light, loose material having a density ranging from .01 g/cc to about 0.3 g/cc (with porosity i.e. air space from 99 to 67% and grain size from 0.01 to 0.5 mm). The atmospheric temperature and solar radiation continuously alter the shape of snow crystals. As new snow falls on top of the residual snow from previous year on the mountains, the total snow becomes thicker year after year until the lower layers are transformed into firm ice (density 0.4 to 0.84 g/cc with porosity ranging from 56 to 8% and grain size from 0.5 to 5 mm) which on further compaction turns into glacier ice (density 0.84 to 0.9 g/cc with porosity from 8 to 0% and grain size from 1mm to more than 100mm). The glacier ice flows with different velocities in different parts of a glacier. It also depends on shape of the glacier and its environment.

For the Himalayas, it is roughly estimated than the 10-20% of the area is covered by glacier ice while an additional area ranging from 30-40% by seasonal snowcover. Himalayan glaciers (including Tibet) cover around 100,000 kmý and the maximum seasonal snow cover could be around 1.5 106 kmý. These fields store about 12000 km3 of fresh water. These enormous snow and ice fields have a significant cooling affect on their immediate neighbourhood and the region as a whole. Some studies indicate that their cooling extends globally. A recent study of ocean sediment core analyses has demonstrated that the Himalayan uplift has sent a cooling signal throughout the globe and even cooled Antarctica. The icy conditions in the Himalayas rival those existing in polar regions and therefore it is sometimes referred as a 'third pole'. Thus, the extensive Himalayan snow and ice fields act as a great refrigerator, cooling the earth's environment. The meltwater contributions from the mountains reorganize oceanic circulations all the time.

Himalayan glaciers are generally classified as longitudinal or transverse glaciers. Longitudinal glaciers occupy structural valleys, along low gradient slopes (6:1 or less) while the transverse glaciers originate from small depressions and flow along steep slopes (gradient 2:1).

EARTH AND ATMOSPHERIC STATUS

Himalayan glacier environment provides a unique platform due to ultra-high altitudes providing rarefied atmospheric conditions in a fragile terrain. Its irregular mountain topography affects atmospheric circulations at all scales of space and time and extensive spread provide changing thermal and moisture regimes. The Himalayan glaciers lie astride the boundary zone between monsoonal and westerly atmospheric influences, strongly affecting the precipitation (rain and snow fall) and hydrological (water flow) conditions in the region. Glaciers in western Himalayas receive more winter accumulations due to westerly disturbances while those in Eastern Himalayas receive more nourishment from the summer monsoon. In the western Himalayan region, the average annual winter precipitation is about 80% and 20% in summer seasons creating arid to semi-arid conditions. The situations reverse in Eastern and North-Eastern region where the average precipitation is 20% in winter and 80% in summer, resulting in humid and per-humid conditions.

Due to large altitudinal distribution of ice fields of over 2000 meters (ranging from less than 4000 m to greater than 6000 m) and a large variations of surface slopes, combination of polar, temperature and tropical conditions are created. Polar i.e. temperature below the freezing point; temperate i.e. temperature corresponding to melting point of ice and tropical i.e. with high temperature and with considerable precipitation. In addition to direct precipitation on the glacier, there are a substantial contributions from snow avalanches from side slopes on these glaciers. The avalanched snow converts into glacier ice in 2 to 4 years while for direct snow mass on glacier, it takes decades to transform into glacier ice. These environmental conditions make the Himalayan glaciers behave in a complex manner. The extra high altitudes of cold environment acts as a great screen in the way of moisture carrying warmer air flows from Indian and Pacific oceans and also from incursions of cold air masses from Atlantic and Arctic regions.

As explained above, a great diversity of earth and atmospheric conditions prevail in the region. This is amply illustrated from the analyses of data collected during decades of observations made in the high altitude region as outlined below:

- The annual precipitation could be from less than 20mm to greater than 5000mm; its variation coefficient is about 20% in the east, 20 to 30% in the north and west and 30% to 70% in the south.
- The higher mountain belt have stable precipitation with a maximum at about 5250m near the equilibrium line - the line or zone on the glacier where a year's ablation (reduction of snow cover by melting, evaporation, wind and avalanches) balances a years accumulation on a glacier.
- The annual evaporation in the glacier region varies from 70 to 120 mm/yr.
- The snowline elevation are higher in the east than in the west.
- Negative temperatures on continental (interior of a continent marked by large annual and daily temperature ranges, low humidity and moderate rainfall) glaciers last over six months compared to three or four months on maritime (adjacent to the sea characterized by small daily or annual temperatures and by high humidity) glaciers.
- The glaciers in the southeastern region are subject to ablation at a rate of 3-6m/yr. which is smaller in the western arid region.
- Solar radiation is the main resource of heat for melting next to induced latent heat (amount of energy absorbed by snow for melting) and accounts for less than five percent.
- The hydrological year for continental glaciers is from September to October, while for maritime glaciers it is from January to December.
- The specific run-off ranges from 25.5 to 61 litres/sec/kmý for continental glaciers while it fluctuates from 85 to 195 litres/sec/kmý for maritime glacier.
- The annual glacier melt is about 50 percent in the west and decreases to about 10 percent in the northeast for the mountain region.
- Rivers with large glaciers areas are less susceptible to the effects of drought or excessive flooding due to the self regulating mechanism of glacier systems as the

glaciers release more water during dry-hot year as compared to a wet-cold year due to more incident solar radiation.

The snow line (lowest altitude of continuous snow cover) is the product of the combined effect of climate, terrain and altitudinal variation. It rises from East to West and from North to South. Changes in snow lines are higher in Eastern part than in Western part of the mountain. On a glacier system in a no change situation, at the equilibrium line, the place where the snow accumulation is equal to the snow ablation as well as to the depth of runoff over the year. The altitude of equilibrium line of Himalayan glaciers increases steadily from 3500-4500m to 5500-5800m at various locations. The climatic conditions that determine the regime and annual value of glacier melting and evaporation exhibit a great diversity in the region. The reason lies in great differences in terms of altitudes (<4000m to >6000m) and latitudes (28øN to 38øN). Moreover, the differences in circulation processes in the northwestern and southeastern parts of the region produce opposite annual regimes of cloudiness, precipitation and air humidity during winter and summer seasons.

Three main types of melting are distinguished in the region: advection i.e. very slow melting when the sky is overcast or the weather is dull; radiation and advection, when the most intensive melting at the rate of up to 100 mm/day occurs, there being few clouds in the sky; and the radiation type, when melting is appreciable on a cold sunny day. By contrast, in the high and Eastern Himalayas, an advection and radiation type of melting occurs during the monsoon period, when slow melting at the rate of 20 mm/day continues daily in conditions of continuous and variable cloudiness and snowfalls. When the monsoon is over, a radiation type of very slow melting is established there. Thus, the snow & ice fields continue to yield meltwater contributions throughout the year.

ROLE OF GLACIERS FOR PERENNIAL RIVER SYSTEMS

Meltwater contributions from snowcovers, glaciers and permafrost (permanently frozen ground) play an important role for generating innumerable streams which feed the perennial river systems of the Himalayan region. It is estimated that more than 8,500 Km3/yr is the total amount of water flowing from the Himalayas to the plains. About 10 percent of this volume of water comes from the meltwater contributions while the rest from intense rainstorms. Due to changes in radiation balance, the meltwater contributions are greater in a drought (warm-dry) year while it reduces in flood (cool-wet) year. Thus, glaciers act as buffers and regulate the runoff water supply from high mountains to the plains during both dry and wet spells which are inherent phenomena in a tropical environment.

Both saline and freshwater natural lakes exist in high altitude region ranging from 600m to 5600m. Out of three major river systems from this world's largest highland-lowland system i.e. Indus, Ganga and Brahmaputra, two i.e. Indus and Brahmaputra originate from the glacial lake systems. The average annual runoff of Indus, Ganga and Brahmaputra rivers are 208, 494 & 510 Km3/yr. Due to higher precipitation at higher elevations and contributions from meltwaters from snow & ice, the specific water yields from the mountain watersheds are higher as compared to river basin as a whole. The water discharges from the mountains in Indus, Ganga and Brahmaputra decreases respectively due to changes in the environmental conditions. This demonstrates the greater importance of mountain glaciers in arid to semi-arid regions (Indus & Ganga) as compared to those in humid and per-humid regions (Brahmaputra).

Large fluctuations of temperature in the higher mountains region generate a strong and severe freeze-thaw cycle, resulting in greater erosion of soil and rock formations. Another important factor for excessive soil erosion is very intense monsoon rainfall (from a few hundred mm to thousands of mm in a day). Measured sediment loads in river water range from less than one ton/ha/yr to over 100 tons/ha/yr. No quantitative estimates are available for bed load sediments which evidently play an important role for the environmental modification of high mountain regions of turbulent streams. In times to come we have to evolve strategies for sediment utilisation and redistribution for efficient water resource management of the mountain waters. It has been observed that the lean periods of Ganga (May and June) coincides with higher flows in Brahmaputra during these months. Linking the two rivers to utilize and harmonize the variations between lean and high flows to avoid distress and conflicts due to drought and floods seems to be a possible and workable solutions.

RECESSION OF GLACIERS

Recession of glaciers is linked up with the warming of the earth' climate. During Pleistocene (about 2 million years back) the glaciers occupied about 30% of the total area of the earth as against 10% at the present. Data on Himalayan glaciers is not sufficient to produce a maximum ice surface reconstruction or to resolve the Pleistocene glaciation. It is now well known that the climatic changes lead to repeated glaciations. The accepted logical approaches for these changes are :

i) known astronomical variations in the orbital elements of the earth (Milankovitch theory),
ii) changes in the energy output from the sun
iii) increase in volcanism that would have thrown more air borne volcanic material into the upper atmosphere (stratosphere) thereby creating a dust veil and lower temperatures. The most recent glaciations reached its maximum advance about 20,000 years ago when the Himalayan snow line was depressed from 600 to 1000 meters lower then the present elevation due to fall of temperatures by 5 to 8øC.

Global warming has already caused a significant glacier ice loss since the Little Ice Age (AD 1550-1850) resulting in both glacier retreat and thinning (loss of ice volume). Catastrophic natural processes triggered by these glacier changes were responsible for considerable death and destruction throughout the mountains. These processes included ice avalanches, landslides and debris flows, outbursts from moraine-dammed lakes and also outbursts from glacier dammed lakes. Glacier avalanches have occurred where glaciers have retreated up steep rock slopes. Land slides caused by debutressing due to glacier thinning include rapid, mobile rock avalanches and non-catastrophic slope deformation. Sources of debris flows are frequently moraine complexes exposed during glacier retreat, which also may be ice-cored. Outbursts from moraine dammed lakes result from the catastrophic breaching of the moraine dam - a process which is commonly initiated by glacier avalanches - generated waves that overtop the moraine. Himalayan and Trans-Himalayan glaciers are in general state of retreat since AD 1850. The average rate of retreat ranges from less than 4 m/yr to more than 40 m/yr depending upon location and the type of the glacier. In Karakoram mountains, there are glaciers which surge i.e. move suddenly at a very high speed. Most of the Himalayan glaciers are covered by debris which slows down their melting.

Glaciers are always active and their activity generates a lot of fresh water and sediments. Over a period of time their erosional and depositional landforms generate spots of great scenic beauty and attraction to mankind. At times they generate huge natural hazards, scaring and distressing all life forms. As the infrastructural facilities increase in the mountain settlements, the mountain hazards damages also increase. Therefore, there is need to monitor high altitude glaciated region to understand the natural processes and the magnitude of natural hazards, for mitigation measures. Suitable blends of traditional and modern concepts are needed, so that loss could be minimized and more harmonious environmental conditions are created in the mountains. This becomes even more important when global warming due to greenhouse effect is knocking our doors and our present scientific knowledge of glacier - climate relationship is insufficient to address the effect and consequences of these climate changes on the high terrain.

GLACIERS

- Glaciers are rivers of ice and are dynamic systems sensitive to their surroundings and constantly change their shape & form.
- Glaciers are classified based on various criteria e.g. morphological (area-altitude), thermal (polar, temperate & subpolar) & dynamic (active - maritime environment at low latitudes & passive - high latitude or in continental environment.
- Glaciers movement is due to internal flow of ice and its slippage over its bedrock. Normally they move a few cms. per day. Warm glaciers move more rapidly as compared to cold glaciers. Increase in velocity results in extending flow and the glacier advances & thins while a decrease in velocity leads to compressive flow and glacier shrinks & thickens. Some glacier surge due to a large and rapid increase is basal slip.
- Mass balance is mainly controlled by changes in a relatively thin ice layer (zone of accumulation and ablation). A positive mass balance results in glacier advance while negative mass balance results in glacier retreat. The glacier advance and retreat modify landscape. It is controlled by pressure, temperature and other micrometeorological elements e.g. radiation, relative humidity, evaporation & wind

direction. Observations on mass balance are required for several years for a representative value for any engineering venture.
- Glacier erosion takes place due to abrasion and bodily moving rock fragments in the glacier mass. Direct evidence of erosion on bedrock is in the form of striae, grooves, smoothing, rounding & sharp truncation of internal rock structure. Large scenic features e.g. u-shaped & hanging valleys, glaciers steps, excavated lakes etc. Undercutting of steep slopes takes place by glacier sapping and glacier milling takes place by circulation of meltwater in the glacier crevasses and depressions.
- Glacier have enormous capacity to transport rock debris. Generally sediments move slowly with speed of 1m/d in ice mass but transport over glacier margin, debris flow, running water & wind operate at much faster speed.
- Depositional features, moraines, erratic outwash plains and trains, ground moraine sheets, drumlin and various ice content features e.g. Kettle holes, kames & esker. Glacio-eolian deposits includes sand dune sheets & mantle of loess (dust). Glacial lake deposits are used for dating paleo-environment. Glacier lake outburst floods occur due to breaking of moraine or glacier dammed lakes.

Notes to readers

The author may be reached at:

Vigyan Prasar C-24
Qutab Institutional Area
New Delhi - 110 016
India
Tel: 91-011-686 5968
Fax: 91-011-696 5986
http://www.vigyanprasar.com