Chapter - 2: Literature Review
Currently rapid climatic changes such as global warming, ozone depletion and environmental pollution related problem have attracted the researchers, scientists, academicians and planners. The change brought on the fragile mountain environment by rapidly expanding population and global climatic changes have deep concern among the environmental scientist (Ives and Messerli, 1989). The applications of the environmental studies on mountainous ecosystem are important primarily because they influence the climate and weather and secondly on account of the fact that they are the major source of one of the most important component of the life supporting system - the water. Perhaps most importantly, about 80% of the planet’s fresh water come from mountains (Barry, 1997). Altogether half of the global population as well as the wide array of plant and animal life rely on mountains watershed for fresh water. The water resources on these mountains provide classic example of human misdeed and short sightedness to reap temporary gains through their over exploitation. The despoiling of the water bodies on the higher mountains are becoming more apparent than the past. Processes of climate change and despoiling of the environment during the recent decade have brought a plethora of environmental disruption of many of these formerly remote, unspoiled water bodies of high mountains to such a extent that they are damaged beyond repair (Hasnain, 1997). It is becoming more apparent that now the mountains are no more metaphor for the reliance, strength and immutability, unfortunately they are crumbling fast eroding mass instead.

In view of importance of these mountain chains for global sustainability, an International Mountain Society has come into existence for protecting the fragile mountain from the threat of human misdeeds on the delicate environment. It is now a matter of international concern and is receiving weightage eversince. The trends of current researches entail the prime concern the study of three principal mountain chains of globe; Alps, Andes and Himalaya. The impressive array of literature of the water system of these mountain chains is provided by (Hynes, 1978; Oglesby, 1970; Carlsen and McCamnn, 1971; Willon, 1975; Hasnain, 1993, 1996, 1998, 1999). However, the knowledge of the water bodies on

2.1 The Himalaya

The word Himalaya is derived from the Sanskrit Hima; snow Alaya; home. It is driven by the ongoing collision between the Indian and the Eurasian plate. The Himalayan ranges are one of the most dynamic mountain chains in the world. It is covered by the snow and glacier due to its latitude, altitude and just located on sub-tropical climatic belt (Upadhyay, 1995; Hasnain, 1999). It comprises of four parallel zones differing in geomorphic, hydrogeographic and vegetation patterns. These are Trans-Himalaya (above 6000m of height), Himadri (Greater Himalaya) between the 4500-6000m, Himachal (Middle Himalaya) between 3000- 4500m and Siwalik (foothills) between 900-1200m of height (Ives and Messerli, 1989). The Greater and Middle Himalaya comprise a sizable area is most active part of the basin in response to intense freeze and thaw cycle combined with active tectonics, high relief, heavy rainfall, glacial erosion and susceptible lithology, which contributes to the intense geomorphologic and hydrological processes in the Himalaya. It makes the Himalaya more prone to natural hazards such as earthquake, landslides, snow avalanches, mudflows, and glacial outburst floods, which offer great challenges in managing the ecohydrology of headwaters (Bahadur, 1998).

2.2 Geomorphological and hydrological processes in Greater and Middle Himalaya

Because of the availability of relief and deep dissected structure, latitudinal and altitudinal variations play an overwhelming role in the landform and hydrological processes in Himalaya. The hydrological and landform processes depend fundamentally on the climatic, vegetational, tectonic conditions, but vary regionally as function of lithological conditions (Gansser, 1983). Broad regional gradient of moisture, temperature and vegetational cover plays most important role for the hydrological and landform processes (Paffenh et al., 1956; Hewitt, 1968a,). Important local variations arise, owing to aspect of wind system, human activity, and the sub-basin location within the watershed. The relationship between the environment and altitude in the mountainous regions has been used as common descriptive
approach to high mountain environments (Price, 1981). Its importance in the Himalayan mountain has been recognized by Paffen et al (1956) and Hewitt (1968a). The Greater and Middle zone of Himalaya contain most of the mountain ridges with glacierised surface. So, the glacier action is of fundamental importance. There are also extensive mountain slopes above 3000m that descend directly to the river gorges. Hence, the geomorphic and hydrological studies in this zone also reflect the larger area that is ice-free area but has seasonal snowcover. However, much of the slope has the glacier or snow at the head or a glacier margin at the base or both.

2.2.1 Glacio-fluvial processes in Greater and Middle Himalaya
The broad controlling factors on geomorphic and hydrological processes in the Himalayan areas, have been described on the basis of area-altitude distributions, and their relationship among precipitation, thermal conditions (includes freeze/thaw cycle), the distribution of snow on ground, and the water yield from the melting of snow and ice (Hewitt, 1968). These conditions are subject to altitudinal gradient in moisture stream from Alpine at high altitude areas to arid lower ones and they are of decisive importance to determine the rate and extent of geomorphological and hydrological activities in the high mountains (Hewitt, 1985). On the basis of these factors, four distinct hydrological and geomorphological zones were identified in the Central Himalaya (Hewitt, 1998), which are summarized below.

Zone 1 (>5500m altitude)
The perennials ice belt, with frigid humid condition, cloudiness and snowfall is heavy throughout the year, but specially in winter. Glaciocinival forms dominate especially in glacier accumulation zones and all season avalanching on slopes.

Zone 2 (>4000-5500m altitude)
A cold but seasonally warm humid belt. It includes the upper and middle ablation zone of glacier, and a mixture of rockfall, Alpine meadows and the tundra conditions. A heavy winter snowfall lies on the ground for 8-11 months. Summer occurs a short vigorous melt season, 2-12 week of diurnal freeze thaw cycle.
Zone 3 (>3000-4000 m altitude)
A cool sub-humid belt with warm summers. A moderate winter snowfall lies on the 3-8 months. Several weeks of diurnal freeze-thaw cycles occur in spring and autumn, and drought in summer. The lower ablation zones of glacier are included, mostly with thick debris cover. Conditions on valley side slopes are montane, gentler slopes support a mixture of forest patches or meadow were not subjected to human activity which has cleared most of the forest area. Heavy summer grazing has helped to give much of the area on dry steep slope. Extensive areas of steep slopes have important seasonal rockfall process.

Zone 4 (<3000 m altitude)
Ephemeral snowfall and 10-12 week of diurnal freeze-thaw cycles. Summers are hot. Gentler slopes are subject to heavy grazing which leaves much bare land. Most of the area is covered by the old glacio-glaciofluvial, slope deposits and veneer of the more recent deposits reflecting moisture-deficient processes. The paraglacial zone involves the reworking and entertainment of sediment by moisture from the higher elevations.

2.3 Glaciers in Himalaya
The world's total glacier area is 16.2 * 10^6 km^2 of which only 0.7 * 10^6 km^2 lie outside the polar region, these are scattered in major mountain ranges. Global glaciers distribution outside the polar region is given in Table-2.1. Perennial snow and ice cover about 43,000 km^2 (Wiesmann, 1956; Agarwal, 1991; Vohra, 1993) on the Himalaya. Thus, glaciers action are of fundamental importance in these regions. The vast glaciers coverage included in two largest components of high Asia glacier complex, the Himalaya and Trans-Himalaya and comprise about 50% area of all glaciers outside of the polar region (Vohra, 1993). There are nearly 15,000 glaciers in the Himalaya lying between the two syntaxial bends of the Hindu Kush-Karakorum ranges and Eastern Himalaya-Patkai Bum ranges. It is reported that 4.0 * 10^5 km^2 of the Himalaya was covered by glaciers during Pleistocene period, whereas, it is only 43,000 km^2 today. Glaciation over the Himalaya began much before the Alps, mainly, due to its high altitude. According to first generation inventory prepared by Geological Survey of India in 1961, Himalaya contains 15,000 glaciers spreading over 43000 km^2. These glaciers mostly belong to Indus, Brahamputra, and Ganga River system. Their sizes
vary from less than 1 km to as large as the Siachin, which is 72 km long. The average depth and speed of the Himalayan glaciers are less than the global mean depth and speed of glaciers (Upadhyay, 1995).

Himalayan glaciers are formed due to successive accumulation of snow layers over a long period of time. Favorable conditions for glacierization over the Himalaya are (I) sufficient snowfall, wind drift deposition of snow in the depression zones and south facing of the Indian Himalaya, (II) low temperatures on the higher mountains restrict the excessive ice melting. There is a marked reduction in snowfall as we proceed towards the central to eastern Himalayas. This results to the higher number of glaciers in the west than that in the east. However, the lee side of the ranges like Lahul Spiti valley or Ladakh region receives very little precipitation. Hence, less number of glaciers in the region. Heavy snowfall areas are windward side of Pirpanjal, and Greater Himalaya results to the higher glacier concentration in this region as compared to other areas. Another region of glaciers are the high reaches of Nanga Parbat, Nunkun, Nanda Devi, Namche etc., where glacierization is favored due to excessive low temperature. The Himalayan glaciers differ from those in the Alps and other latitude zone in the following features (Upadhyay, 1995; Agata, 1978).

(A) Debris cover over the glacier surface on Himalayan glacier is denser particularly in ablation zone. Dust spread is also more as a consequence of mechanical destruction of rocks and boulders. In addition, there is a significant quantity of biomass and bacterial spread over the surface of Himalayan glaciers. Hence, these glaciers have blackish, brownish or unshining look as compared to mountain glaciers at higher latitude in Alps. Surface albedo is markedly reduced by 10 -20% or even less on many glaciers covered with black rocks or dark debris.

(B) Summer temperature over the Himalayan glaciers is higher as compared to glacier at the other latitude of Himalaya, particularly on southern slopes. It is usually above $10^0$ C. Occasionally temperature of $18^0 - 22^0$ C is also experienced by glacier portion resting on lower altitude. Hence, the snow or firm layer of glacier possesses more liquid water content. Both the features tend to enhance melt rate resulting into large water yield runoff in the Himalayan rivers.
Table 2.1: Global glaciers distribution outside the polar region.

<table>
<thead>
<tr>
<th>Continent</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>23000</td>
</tr>
<tr>
<td>North America</td>
<td>68000</td>
</tr>
<tr>
<td>South America</td>
<td>19000</td>
</tr>
<tr>
<td>Africa, New Zealand, Tasmania</td>
<td>22</td>
</tr>
<tr>
<td>Asia</td>
<td>120,000</td>
</tr>
</tbody>
</table>

Source: (Upadhyay, 1995)

2.4 Recession of Himalayan glaciers

Most of the Himalayan glaciers show the general trend of retreating, but in case of a few of them, advancing has also been observed. Behavior of the transverse glaciers is much more complex than the longitudinal glaciers; it may be due to the fact that these are 'shorter' and flow is perpendicular to the incoming circulation pattern and have steeper gradient (Mayewski, 1979). This may be due to global warming and human interference. The Himalayan glaciers are mainly of surging type that are capable of causing floods, slides and avalanches. In the processes, their recession may get accelerated. The retreat of some of the Himalayan glaciers is given in Table-2.2.

Table 2.2: Retreat of the some Himalayan glaciers.

<table>
<thead>
<tr>
<th>Glacier and location</th>
<th>Period of observation</th>
<th>Retreat(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinderi (U.P)</td>
<td>1845-1966</td>
<td>2840</td>
</tr>
<tr>
<td>Milam (U.P)</td>
<td>1849-1957</td>
<td>1350</td>
</tr>
<tr>
<td>Shaunkulpta (J.K)</td>
<td>1881-1965</td>
<td>518</td>
</tr>
<tr>
<td>Zemu (Sikkum)</td>
<td>1909-1965</td>
<td>44</td>
</tr>
<tr>
<td>Gangotri (U.P)</td>
<td>1935-1976</td>
<td>600</td>
</tr>
<tr>
<td>Bara Shigri (H.P)</td>
<td>1892-1945</td>
<td>1100</td>
</tr>
</tbody>
</table>

Source: (Upadhyay, 1995)
2.5 Impact of future climate change on the snow, ice and glaciers

Output from the general circulation model of Greca et al (1994) were applied to the major cryosphere region of the world in order to assess the potential effect of global temperature rise by the 2050 A.D. They predicted that the most of the region from cryosphere will warm by 0.5 - 2.5 °C (IPPC, 1996), some area will be wetter and other drier. Continental snow cover will be diminished in extent, duration and depth. Winter snowline could move further north by the $5 \times 10^4$ latitude. Thus, snowfall will begin later and snowmelt will be earlier than at present so that the snow free period will be extended. In Alpine area the snow line could rise 100 - 400 metre depending on the precipitation. There is a tendency for rainfall to occur at the expense of snowfall. It is showed as a results that 1 °C increase in temperature of snowcover area would be depleted in winter snowfall due to conversion of precipitation to rainfall and increased snowmelt in glaciers (Kadota, 1997).

Both empirical and energy balance models both indicate, that a large fraction of present existing mountain glacier areas could disappear with anticipated warming over the next 100 years. In addition the high rate of accumulation and ablation, rapid response to climate change may cause a significant effect contribution to sustainable water supply. The results of Grece et al (1994) model also indicated, that some mountain area will experience increase in precipitation. The model demonstrated changes in the precipitation mass balance of glaciers would become negative rather than positive, glacier will likely to shrink even when mountains become wetter. An upward shift of the equilibrium line by some 200-300 m and annual thickness losses of 1 to 2 meter are expected for the temperate glaciers. Many mountain chains will lose major part of the glacier cover with in the decades. However, the larger Alpine glacier such as those found around the Alaska to Karakorum, Pamir and the Himalaya may continue to exist in the 21st century. The high altitude and latitude snow and glacier may show little change, but the warming of the firm areas will be pronounced. Their mass balance may be affected through enhanced ablation at low altitude and latitude, while accumulation at the higher could increase. There will be pronounced influence on the runoff from glacier melt as a result of climate change. Glacier melting will provide extra runoff as the ice disappear and the deglaciation on the high mountain. These will leave the moraine deposits unprotected against erosion for extended time period. There will be increase in the sediment load in Alpine rivers and accelerated sedimentation in the lakes and the artificial
reservoirs at high altitude. On the slopes steeper than about 25-35° stability problem such as debries flow will develop in freshly unconsolidated sediments. So, that massive rockslides will occur in the deglaciation valley. Lakes dammed by snow, side moraines and glaciers can suddenly produce floods or debris flow in order of magnitude larger than normal stream flow. Pressure related to ice retreat such as glacier avalanches, slope instability caused by distressing and glacier floods or ice dammed lakes may pose a hazard to the people, transport route and economic infrastructure on the mountain areas.

2.6 Availability of fresh water in the India Himalaya

Total area of the India is $3.28 \times 10^6$ km$^2$ and annual normal rainfall is 117 cm. Hence, volume of rainwater is 3838 km$^3$ per year. It is a huge quantity, but its distribution in time and space is erratic. Rainfall is concentrated in the four month of monsoon. Floods and droughts are regular features in the region, because of such uneven distribution pattern. Thus, monsoon rain is a good producer of fresh water, but poor distributor in the Indian subcontinent. If one compares the runoff generated from the snowmelt and glacier melt from Indian Himalaya, it comes about 5% percent of the total rainfall of the country (Upadhyay, 1995; Bahadur, 1993). It shows that snow and glacier melting are poor producers of fresh water, but good distributors as they yield at the time of need. It has been estimated, that the about the 3870 km$^3$ of fresh water is locked in the Himalayan glaciers spreading over 43,000 km$^2$. Based on the meteorological data, snow and glacier melting over Himalaya shows that 670 km$^3$ volume of water in Indian comes from the Himalaya. The annual water availability from the Himalayan region has been given in Table-2.3.

Table 2.3: Annual water availability from the Himalayan region to India.

<table>
<thead>
<tr>
<th>Source</th>
<th>Volume of water (km$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glacier</td>
<td>40</td>
</tr>
<tr>
<td>Seasonal snow</td>
<td>160</td>
</tr>
<tr>
<td>Rainfall</td>
<td>470</td>
</tr>
</tbody>
</table>

Source (Upadhyay, 1995)
Processes operating in the higher mountainous catchment

The altitudinal variation plays an overwhelming role in the hydrological processes in Himalaya. Broadly regional gradient of moisture availability, temperature and vegetational cover play the most important role for determining the hydrological processes (Paffen et al., 1956; Hewitt, 1968a). The relationship among different hydrological and geomorphological processes on basis of altitude in the mountainous regions has been used as common descriptive approach to classify high mountain environments (Price, 1981). On the basis of the vegetation pattern and ecosystem characteristics, the high Himalayan ecosystem can be divided into three main ecosystems; [ (I) Alpine catchment, (II) Plateau and Meadow, (III) Forest catchment]. The characteristics and processes operating in these ecosystems are described below.

2.7 Processes operating in the Alpine catchment

Glacial, fluvial and weathering processes, which are active agents of weathering and erosion in Alpine environment, are discussed in this section. Several other factors like climate and relief influence the intensity of these processes from time to time. These processes are interdependent on each other and can not be treated in isolation (Fenn, 1987).

2.7.1 Chemical weathering

The studies on the chemistry of meltwater emerging from the glacier portal indicate that the chemical weathering is more intense in these regions (Rainwater and Guy, 1961; Reynolds and Johnson, 1972; Slatt, 1972; Souchez and Lorrain, 1978; Church, 1974; Collins, 1977, 1979a, b, 1995; Lemmens and Roger, 1978; Eyles et al., 1982; Tranter et al., 1986, 1989, 1991; Brown et al., 1993, 1996; Sharp et al. 1995). By virtue of the fact that the temperate glacial environment represents an extreme of hydrological condition, it may, therefore, represent an extreme of chemical weathering activity even in the absence of normal biologic and pedogenic processes associated with the soil (Reynolds and Johnson, 1972). Evidently the low average temperatures generally associated with an active glacier do not inhibit chemical weathering reactions. The flowing water plays an important role in the dissolution and evacuation of minerals from glacierised
catchments. Fenn (1987) proposed following mechanisms by which minerals are converted into ionic species:

1. Solution - Dissociation and evacuation of soluble ions from minerals (water acts as a solvent).

2. Hydrolysis - Hydrogen ions dissociated from water replace mineral cations, leading to the expansion and decomposition of mineral structures. The displaced mineral ions may combine with the free hydroxides to form a solution (water as a reactant).

3. Carbonation - Soluble products (and insoluble residues) produced by reaction between the mineral and the carbonate and bicarbonate ions contribute to water by the absorption of atmospheric CO$_2$.

4. Hydration - Absorption of water into mineral lattices, causing volumetric changes promoting disintegration and/or decomposition (water acts as a catalyst).

5. Oxidation - Combination of a mineral with dissolved oxygen to form oxides or hydroxides, weakening the original mineral structure.

6. Reduction - Addition of an electron to the elements of a mineral under anaerobic conditions, resulting in a change in susceptibility to decomposition.

7. Cation exchange - One-to-one interchange of cations between a water film rich in one cation and a mineral rich in another cation.

2.7.1.1

Reynolds and Jonhson (1972) from their work in the Cascade Mountain concluded that, carbonation was an important mechanism controlling water chemistry. This is further supported by several studies like (Tranter and Raiswell, 1991; Tranter et al., 1989; Brown et al., 1993, 1996; Sharp et al. 1995). In the carbonation reactions atmospheric carbon dioxide reacts with water to form weak carbonic acid (H$_2$CO$_3$). Carbonic acid is unstable and soon breaks down to give H$^+$ and HCO$_3^-$ ions. Thus, the H$^+$ ions released in this process react with the silicate minerals and in the process releases the cations, dissolved silica and clay minerals to the water. The low temperatures and the turbulent nature of the meltwater stream provide ample opportunity for continuous resaturation of water with CO$_2$. The increased solubility of CO$_2$ in cold waters indicates that carbonation reactions will proceed more vigorously in colder regions than under moderate environmental conditions. Sulphide minerals are highly reactive with water.
under oxidizing conditions. So, these minerals release their constituent ions to water as soon as it comes in contact with them. Higher dissolution of atmospheric $O_2$ in turbulent and well-aerated water in Alpine environments promotes the oxidation reactions by constantly exposing the fresh rock surface to the water.

2.7.1.2 Ion exchange and sorption

Gorham (1961) briefly described the role of ion exchange and sorption mechanism in the supply of major ions to inland waters. Cation exchange appears to be an essential mechanism in the explanation of dissolved cation content of meltwaters in the frontal zone of glaciers (Lorrain and Souchez, 1972; Lemmens and Roger, 1978). In the cation exchange processes, the sorbed cations in the clay-layer around the particles will be replaced by $H^+$ ions present in water. Lemmens and Roger (1978) concluded from their work on Alpine glaciers, that alkalis sorbed on the surface of the suspended and bed sediments are exchanged with the hydrogen ions in the water. This phenomenon is favored by the presence of fresh material with a high abundance of clayey particles having larger surface area and the longer time of contact between water and morainic material. The rate of exchange is dependent on the gradient between the guoy layer and concentration of cations in water and also on the cations involved, for example, $K^+$ diffuses more quickly than $Na^+$ and that $Mg^{2+}$ is the slowest. Later, surface rather than ion exchange is the term used for these reactions because although a reaction is rapid, it is largely irreversible unlike ion exchange, which is reversible (Susenberg and Clemency, 1976;). The surface of the mineral may be physically altered during surface ion exchange (Casey and Bunker, 1990) rendering, it difficult to replace (or exchange) the adsorbed protons for dissolved base cations (Garrels and Howard, 1956). Unlike ion exchange, this type of exchange is said to be specific, since a chemical bond is formed between the mineral surface and the adsorbed ion. Surface ion exchange has a marked effect on the ability of the solution to dissolved $CO_2$ (Tranter et al., 1991).

2.7.1.3 Pressure melting and relegation

Several studies have revealed that Alpine glaciers often have a basal ice layer which is different in texture, structure, chemical and isotopic composition (Tison and Lorrain,
Formation of this basal ice layer at the sole of temperate glaciers explains the melting and relegation during sliding of glaciers over small obstacles (Hallet, 1976a). The sole of the moving glacier exerts pressure on the stoss side of the obstacle. Temperature gradient also occurs because the melting of water on stoss side takes heat from the surrounding and recrystallisation on the lee side releases heat to the surrounding. Because of the pressure gradient the meltwater moves to the lee side of the obstacle, where relegation takes place at reduced pressures and higher temperature.

During relegation the freezing ice will repel the dissolved constituents, so that the remaining water gets enriched with solutes. When this water reaches oversaturation the excess gets precipitated. Widespread deposits of calcite precipitated over the till vacated by glaciers were reported by Hallet and others (1978) from an area around castleguard in the Rocky Mountains of Canada. Comparatively, silica precipitates are less known, but one such deposit was reported by Hallet (1976) from an area around Paradise glacier, Washington, USA. These deposits were formed at a very shallow depth, not exceeding few centimeters in any case, and the ultra-fine foreign particles (glacier flour) associated with them might have played seed part. To get precipitated, the water should get oversaturated with the required component and in case of silica it reaches oversaturation at a concentration of 80 ppm at 0°C (Krauskopf, 1956). These relatively widespread deposits indicate that the chemical transport is an active subglacial process and the solute concentrations are higher than saturation point in these waters (Hallet, 1976). Keller and Reesman (1963), have reported as high as 8 mg/l of dissolved silica concentration in Emmens and Nisquilly glacial milk, Mt. Rainier, USA. In the Canadian Arctic, Apollonio (1973) reported greater dissolved silica concentrations in a glacierised Fjord than an unglaciated one.

2.7.1.4 Leaching from ice

The studies on ice indicate that the concentration of dissolved species decreases with depth (Brimbliscombe et al., 1986; Tranter et al., 1986, Reynold et al., 1978). According to Bouard (1977), temperate ice is a complicated material consisting of a solid and liquid phase in thermodynamic equilibrium and whose chemical properties evolve with time.
Ice purification takes place during refreezing of water passing through veins in the glacier, similar to the formation of basal layer. Ions are flushed out of ice during this process. Based on fractional experiments, Souchez and Tison (1978) found that the flushing is selective and alkali metals are more easily flushed out than the alkaline earth metals and a systematic decrease in cationic content of melted water takes place with the progress of time. Leaching of dissolved ions from the ice causes decrease in dissolved solids with depth. So, older the ice, less will be the concentration because of more and more leaching. However, Gorham (1958) has reported no leaching in the ice with depth. However, the concentration profile observed in the study of ice from Blue glacier, Washington, USA was attributed to increased pollution levels by Harrison and Raymond (1976). However, studies on snow indicate that the concentration increases with depth. This may be caused by leaching of ions in to older snow during freeze-thaw cycles (Colbeck, 1981).

2.5.1.5 Channels in glaciers

Water is conducted through glacier in three types of channels viz. supraglacial (on the surface of the glacier), englacial (within the body of the glacier) and subglacial (below the glacier at the ice-rock interface). Shreve (1972) compared these channels with the channel network in the karst region. Collins (1979) envisaged two principal drainage routeways through a glacier- a system of major channels which allows rapid transit and isolates water from potential solute sources, and a system which permits much slower transit and brings waters into contact with solute sources. The first he defined as the englacial and the second as the subglacial component. Widening of the englacial and subglacial channels take place by increased melting because of the pressure exerted by the melting ice above the rock surface. Water flowing in channels inside a glacier produces fractional heat, which causes melting of the ice walls (Röthlisberger, 1972). According to him, subglacial streams may cut deep channels in the bedrock, where closure will be reduced. But it is difficult, as often the course of the stream changes. The widening and narrow down of channels in response to changes in melting rate was also discussed by Fountain (1992) in the study of meltwater draining from South Cascade glacier, Washington, USA. Although, theoretical analyses of glacier hydrology now
identify at least seven possible components to subglacial and englacial drainage system. These includes englacial conduit, subglacial water films (Weertman, 1972), R-channels incised upwards into the glacier sole (Rothlisberger, 1972), Nye channels incised into the bedrock (Nye, 1973), linked cavity system (Walder, 1986), permeable subglacial sediments (Shoemaker, 1986), and broad canals incised into the surface such sediments (Walder and Fowler, 1994). However, according to Tranter and others (1993), this use of the terms subglacial and englacial to describe the flow component is misleading, since both can apparently drain through channels located at the glacier bed. The actual basis for distinguishing between the two components is the residence time of meltwater at the glacier bed rather than their location and morphology. In this sense, it would seem more logical to differentiate between the components; using terms such as delayed flow and quick flow.

2.7.1.6 Water flow rate
The influence of water flow rate on solute acquisition can be assessed by considering the equilibrium constants of silicate and aluminosilicate weathering reactions. Raiswell (1984) suggested that the equilibrium constants for these reactions were of a similar magnitude, indicating that only small increase in the concentrations of the aqueous products (and decrease in $H^+$) are needed to approach equilibrium and stabilize the solid phases. The high flow rates of water have the effect of supplying $H^+$ ions to the water and flushing away the dissolved products of weathering, and preventing the approach to equilibrium.

2.7.1.7 Glacial meltwater
Glaciers produce huge amounts of fine-grained sediment by mechanical erosion. This is the major source of suspended sediment in the meltwater streams. Because subglacial and englacial channels are enclosed on all sides, the water in them will be under tremendous pressure. So the flow will always be turbulent and the routing by this turbulent meltwater exposes the fresh rock surface and also removes lot of sediment in suspension. Because of fine size and high concentration, it gives cloudy appearance to the meltwater. The amount of suspended matter in glacial meltwater is controlled by the character of the rock eroded, glacial abrasion, and glacial melting (Keller and Reesman,
1963). The discharge and amount of suspended sediment varies from year to year depending on variable rates of supply of total sediment to the stream network, the fluctuation in significance to different sediment source areas, and routing of sediment through the stream network (Gurnell, 1982). Higher flow will also flushout the ions released into water and prevent building up of ions, thus promoting further dissolution. Finer the particle, higher will be the surface area in contact with water; more will be the dissolution of material. It is also evident that greater concentration of sediment in water promotes higher dissolution for the same reason. On the basis of laboratory and field data, Eyles and others (1982) found that release of silica from suspended glacial rock flour is important mechanism acting in water of glaciated basins. Suspended sediment is an important source of solutes in water draining from active glaciers (Collins, 1979b). Partial dissolution of suspended particles release ions into water (Slatt, 1972). Major cations may also be transported as sorbed ions on the surface of suspended sediment particles. Extended contact with fines in the bed makes the meltwater richer in solutes, because the increase of surface area in contact with water promotes ion exchange (Lemmens and Roger, 1978).

2.7.2 Physical weathering

In glacierised catchments, physical weathering processes have long been recognized as important in the production of sediments in huge quantities. Embleton and King (1975) have observed a five-fold difference in sediment yield between the glacierised Hoffelsjökull River in Iceland and a nearby non-glacier fed river. Number of studies have demonstrated that specific sediment yield may increase downstream due to remobilization of sediments pushed by the active glaciers (Ferguson, 1984; Warburton, 1990). A survey of sediment yield from 1358 drainage basins with area ranging from 350 to 1,00,000 sq. km, Jansson (1988) found that within particular climatic zones where glaciers are active, sediment yield tends to be higher. Harbor and Warburton (1993) remarked that rates of erosion are higher for glaciers than non-glacial processes. The presences of highly unsorted deposits found in the areas vacated by the glaciers are an indication to the potential of glaciers in the production of the sediment. Plucking, quarrying, crushing, shearing and abrasion are the physical weathering processes in the Alpine basin. It is along the sides and base that erosion and most depositions occur.
(Embleton and King, 1975). Refreezing of water in the low pressure areas at the sole of the glacier causes entrainment of debris in the ice layer. Incorporated debris is carried down by the glacier and it acts more or less like a sand paper (Souchez and Tison, 1981). The debris carried by the sole of the glacier abrades the bedrock and morainic material at the bottom and sides of the glacier and produces fine sediments. Ostrem (1975) suggest that actual glacier may be accompanied uniformly and steadily by the evacuation of sediments from a glacier and depends very much on the amount of water draining through the glacier. This partly substantiates (Embleton and King, 1975) the finding that sediment yields from beneath ice sheets in Arctic areas are lower than yields from temperate glaciers, since the cold in the Arctic allows for little runoff to flush sediments from the glaciers.

2.8 Processes operating in the meadow

Meadows are the relatively flat topography formed by the earlier glacier activities and later on stabilised by the vegetation over a period of time. During winter, this area is covered by seasonal snow, whereas in summer only light showers in the region (Singh et al., 1994). The soil is sufficiently moisture saturated to support vegetation throughout the year. However, cold climatic and high wind conditions do not favour the tree type of vegetation except the few grasses. The ground water storage get develop due to its flat nature and soil type in the region (Freeze, 1972). Ground water and overland flow from the meadow augment into the Alpine-Sub-alpine stream as the Alpine stream passes through meadow. The characteristic water flow contribution from the meadows to Alpine stream changes with seasons. The high quantity of surface water is contributed during early ablation due to overland flow of meltwater over the ice (Marsh, 1978). From hydrological point, the meadow release much water but relatively sediment free (Dunn, 1978), and he has also concluded that the meadow have a moderate soil loss, rather than others landform. The studies carried out on the soil losses from the different geomorphologic unit showed that a herbaceous cover over the meadow acts like a semi-pervious-layer and hinders the immediate infiltration of water into the soil, which result in high quantity of sediment free overland flow. The relationship between precipitation and runoff from meadow is clearly exponential in the most of the meadow's region (Freeze, 1972, Rawat, 1984). Generally most
of rainwater is absorbed, once the threshold is surpassed, runoff starts and increases with higher values as precipitation increases (Dunn, 1978).

The moderately moist climate, low gradient slopes and high clayey soil do not favour the production of sediments in the region. The sediment is produced in the system as a result of various activities such as frost action, vegetation, freeze/thaw cycles etc. Other processes such as seasonal animal grazing also disturbs the soil structure and releases soil particles from the topsoil. In early summer freeze/thaw processes in temporary permafrost soil flushes out the sediment along with the overland flow, which contribute into Alpine stream (Ostrem, 1975; Gurnell, 1982). After the exhaustion of material, contribution of sediment from meadow to stream is negligible. During the rest of the year, only groundwater from meadows contribute into the Alpine stream.

The hydrochemistry of runoff from meadow is mainly controlled by hydrometeorological conditions, which varies with the seasons. Hydrochemical characteristics of water are controlled by wet and dry fall, interaction of atmospheric precipitation with grass, root of plants, micro-organisms and ion exchange within soil. Dry fall in the higher Himalaya may be a major contributor of chemical to the system that is received from fresh rock surface and moraine (Zeman and Slymaker, 1975; Collins, 1979). The exchange of various chemical constituents takes place between plant and precipitation, changes the chemical characteristics of the precipitation after passing of water through plant cover (Abraham et al., 1977; Jeffry and Synder 1981; Liken et al., 1977, Steven et al., 1968). The chemical constituents in rainfall, snowfall and throughfall changes as it come into contact of meadow floor, where more ions are added to surface water and further increase solute in the overland and infiltrate flow. As surface water starts moving down through mineral soil to the groundwater, the solute decreases probably due to the loss of ions to soil exchange complex and biological uptake (Grier and Cole 1972; Feller, 1977).

\[ \text{\textcopyright 2021} \]
2.9 Processes operating in the Sub-alpine forest catchment

The vegetation plays an important role in determining the hydrological cycle in any ecosystem and govern the quantity and quality of surface and subsurface water. The vegetational and hydrological processes are greatly influenced by altitude. The general processes associated with vegetation, which have predominant effect on local hydrology, are interception and evapotranspiration. The moisture extraction from the soil surface through the plant cover determines the formation of different runoff components. The infiltration and interception are also very high and does not allow the overland flow due to high percentage of humus and litter content in the soil horizon of Central Himalayan forest (Freez, 1972; Warring et al., 1981). It is generally seen that as a consequence of high precipitation and lower temperature, water availability increases for plant. However, the high evapotranspiration and steep slopes may facilitate the groundwater movement to the down slope strata in the system, that may results into low groundwater storage capacity in the region than in the forest of flat terrain. Thus, any disruption in climate and ecology of the region may cause more intense stresses on mountainous forest ecosystem than in forest of plains. The conifer forest ecosystem in Central Himalaya is the most productive and fragile in the world due to it's climatic conditions, steepness and altitude (Singh et al., 1994). Thus, any change in environmental conditions may effect largely the global as well as local sustainability of the region.

Frost action, gravity fall, freeze/thaw and biological activities are the main processes of sediment production in the forest catchment. The microbes and various others organisms in the soil contribute intense weathering in the ecosystem. The organic acid production in the ecosystem leaches out the cations from the grain boundary of the minerals. The actions of the acid on the corners of the crystal destroy the framework of rock and they become susceptible to erosion. Frost action further accelerates the process of physical weathering. Land use practices also play a decisive role in soil erosion and water conservation, particularly in the mountainous areas (Ives and Messerli, 1989; Dunn et al., 1978). Several studies focussing on sediment transport and water yield in forest catchments have emphasised the role of an effective vegetational cover, which dissipates much of the raindrop energy and promotes
rates of infiltration and consequently groundwater in the region. In Himalayan mountains, as a consequence of forest cover loss, coupled with the influence of the monsoon pattern of rainfall, the fragile catchments have become prone to low water retention and high soil loss associated with high runoff (Rawat and Rawat, 1994).

The water that reaches the forest floor is vastly different in chemical content than the incident precipitation. These throughfall, atmospheric precipitation and stemflow further change after come in contact with upper soil layer and is called as soil solution. The chemical composition of soil solution and groundwater depends on a complex series of equilibrium, adsorption, displacement, immobilisation, weathering and decomposition. Change in soil solution chemistry depends on a series of relationships between the biological and physical components of the system. Firstly elements are changed into readily leachable compound through biological decomposition and mineral weathering. These forms may be immobilised by biological uptake or adsorption reaction in the forest and controls the hydrochemistry in stream. (Feller, 1977).

2.9.1 Controlling mechanism of hydrochemistry for Sub-alpine forest stream

Based on observations and numerous studies of water quality on the mountainous stream, it has been revealed that, hydrochemistry varies to different degrees and in several contrasting ways for different group of elements (Neals et al., 1990, 1992, 1997; Hasnain, 1994; Baron et al., 1990; Bond, 1979; Deithier, 1979; Feller, 1977). On the basis of the underlying mechanism of variations of the group, together they may be classified as (a) Snowpack related variations; (b) Rainfall related variations; (c) Flow-related variations; (d) Biota related variations; (e) Anthropological related variations.

(a) Snowpack related variations

Snowpack stays for a long time on the ground surface during the winter. As temperature increases, leaching of preferential ion onset in concentrate meltwater by pack weathering (Johannessen and Henricksen, 1978; Cadle et al., 1984; Semkin and Jefferies, 1988), which result in high concentration of $\text{SO}_4^{2-}, \text{K}^+, \text{NO}_3^-$, $\text{H}^+$ ions into the early melt. The percolation of the dilute meltwater into the soil also develops the pressure on the soil solution and result to the flushing out of old groundwater from the soil into the stream. The flushing of old soil
solution increases the concentration of solute in the early ablation period along with the accumulated high nitrate and weathering product of winter (Driscoll et al., 1987; Stotlemeyer and Toczydlowski, 1990).

(b) Rainfall related variations
One might anticipate large variations in concentration of sea salt component in stream water during the storm event. But, the several studies have been showed that, this did not observed in the conifer and temperate forest streams even for components such as chloride, which are chemically unreactive. Neals et al (1990, 92) have been come to conclusion that the forest catchments have the ability to dampen the rainfall's chemical imprints to a very considerable degree. In other words, rainfall does not pass directly through the catchment to provide the major volume of water in the stream during hydrographic response, which is due part of fact that groundwater is the main source of water in the forest streams.

(c) Flow - related variations
On the basis of studies of various forest stream by Baron (1990), Brikenes et al. (1986), Bredemeire (1988), Bond (1979), Beven (1982), Billett (1996), Bormann (1979), Brimblishecombe et al (1986). They have been concluded that the quality of stream water changes with the hydrological response. In winter, the stream flow is dominated by base flow. Storm flow water in contrast has higher $H^+$, Al, $SiO_2$ ion concentration than their base flow counterpart. Change in the stream water chemistry is due to the differential contribution of surface and subsurface water.

(d) Biota related variations
The nutrients and some trace elements show in part broad seasonal variation in forest stream water. Oscillatory peak and trough in concentration, as a function of season, The changes have been well described in terms of temperature-induced biological responses; tree growth, micro-organisms and organic matter decomposition / build up reactions (Blackie and Newson, 1986; Reuss and Johnson 1987; Stotlemeyer et al., 1987).

(e) Anthropogenic related variations
The disturbances in the forest can reduce transpiration and increase the runoff, erosion and leaching (Likene, 1977; Swank, 1988) and associated efflux of solute in particular N, S and
It can alter the surface water quality (Bayley & Schindler 1991). The comparison of overland flow, soil nutrients and precipitation in various land uses suggests that replacement of steep slope forest by agricultural land promotes the erosion of soil, water and soil acidification due to overland flow from the dissolution of organic and inorganic fertilizer in Himalayan catchment (Collin, 1998).

2.10 Hydrological processes in Ganga Headwater

Ganga ecosystem has been a subject of intense inquiries and studies in the recent years (Billgrami, 1985). Scientists from different institutes have collected enormous information about the physico-chemical and biological water quality of this river. The headwater of this river lies in Garhwal Himalaya between 29°45' - 31°30'N and 78°2' - 80°7'E encompassing an area of 30,000 km². This region contains more than 1020 large and small glaciers (Vohra, 1981). The Bhagirathi and the Alaknanda - the two major proglacial streams in the Garhwal mountain constitute the main drainage, both streams confluence together at Devprayag and form the Ganga River. Both streams emerge from the catchments of large valley glaciers where Chaukhamba group of peaks reaches a maximum of 7138m. Bhagirathi River rises at the Gangotri glacier portal known as Goumukh, at an elevation of 4000m, on the northwestern face of Chaukhamba peak, whereas Alaknanda emerges from the twin glaciers of Satopanth and Bhagirathi Kharak at an altitude of 3800m, on the southeastern side of the range. The Ganga River after a run of 280 km cuts through the Himalaya reaches at near Rishikesh and turns southwest for another 30 km and finally descends to the vast Indo-Gangetic plains at Haridwar. The drainage map of the Ganga headwater in Himalayan mountain is shown in Fig. 2.1.

The average precipitation in the Garhwal Himalaya varies between 1000 to 2500 mm, out of which 50 to 80 per cent comes down during the monsoon period. The proportion of snow and rainfall varies with altitude; the Zeheng Benxing (1989) has reported the occurrence of Indian monsoon rainfall even near the 6000m altitude on glacier also. The catchment has an extreme variability of precipitation and energy input. This is reflected in the diurnal and seasonal variations in climate and, hence, the variations in hydrology. Maximum flow takes place between July to September, when rainfall rates are also at a maximum. The Himalayan proglacial streams carry about 70 to 85 percent of their annual flow during the
Fig 2.1: Drainage map of the Ganga Headwater
summer monsoon months in response to the monsoonal precipitation, snow and glacier ice melting (Bruijnzeel and Bremmer, 1989; Hasnain, 1999; Hasnain and Collins, 1995). The seasonal and diurnal variation in hydrology of the stream has been explained by two component mixing modal (Collins, 1977; Hasnain, 1994, 1995). The flow in glacier fed streams is characterised by the relative subglacial, englacial and supraglacial meltwater contribution. The relative contribution of the englacial, supraglacial and subglacial meltwater changes with the availability of the solar radiation (Rainwater and Guy, 1961; Lorrain and Souchez, 1972; Collins, 1977, 1979a, 1979b; Hasnain, 1992, 1993). The study carried out by Hasnain et al (1994) on the Garhwal glacier found that during August-September englacial meltwater contribute around 65% of total flow in the stream and the remaining comes from the subglacial meltwater contribution. This proportion started decreasing in the following winter due to closer of the englacial channel and the contribution of the subglacial meltwater dominates the flow regime in following winter.

The runoff characteristics of the glacierised stream in the Garhwal are highly influenced by monsoonal activity. On seasonal scale, it is shown that the reduction in energy input for glacier melting by cloud cover is not fully compensated by the precipitation in monsoon period. However, the response of the rainfall event on runoff is controlled by the intensity and the distribution pattern of monsoonal precipitation as well as the subglacial drainage characteristics and cloud cover (Hasnain, 1998). Study carried out by Hasnain et al (1998); on a Dokriani glacier in Garhwal Himalaya showed that during the ablation period of 1994, total discharge of glacial stream was $6.38 \times 10^6$ m$^3$ in which only 11% was contributed by the rainfall. The rest of the increased runoff in the stream was due to the summer precipitation on the glacier, which enhance the melting processes in the firm zone of glacier.

2.11 Transportation of sediments in the Ganga Headwater

The Central Himalaya is the world's steepest and highest mountain chain on the earth, which has been driven as a result of collision between Indian and Asian plate. The height and the steepness of the system has made it susceptible to rapid physical weathering and erosion, which produces large quantities of sediments in the region, that is carried by the river further down towards the ocean. This area though represents only 5 percent of the earth's land surface but, supplies 25 percent of the sediment load to the world oceans (Raymo and
Ruddiman, 1992). Current estimates of sediment yield of the Ganga and the Brahmaputra Rivers together is about $4.0 \times 10^9$ tons year$^{-1}$ (Subramanian, 1993), compared with the global annual sediment flux of about $15 \times 10^9$ tons year$^{-1}$ (Milliman and Meade, 1983). Contemporary rate of denudation in the Himalaya is undoubtedly very high in comparison with continental averages, as might be expected in an area of recent and continuing tectonic activity. The ongoing interaction of Indian and Eurasian plates maintain uplift, the high relief and large glaciers along with unstable steep slopes maintain sediment supply to the rivers of the subcontinent (Collins and Hasnain, 1995).

The sediment transports in the Himalayan glacial streams show the seasonal and diurnal variation in response to the relative contribution of the supraglacial, englacial and subglacial meltwater characteristics (Hasnain and Chauhan, 1992; Hasnain and Thayyen, 1996). The suspended sediment concentration in the streams also show the seasonal and diurnal variation, maximum suspended sediment concentration is recorded with high flow and minimum with lowest flow. The hysteresis between the suspended sediment concentration and discharge is also observed, that can be explained by flushing of sediment from the glacier surface, after receiving the first rainfall (Collins, 1989, 1990; Hasnain et al., 1994, Ostrem, 1975; Gurnell, 1982). However, the nature of hysteresis was observed to be different in the Pre-monsoon and Post-monsoon period due to relative contribution of supraglacial, englacial and subglacial routing and flushing. The relative contribution of supraglacial, englacial and subglacial routing depends on the available seasonal energy variation in the system (Hasnain, 1995). In the early ablation period, some of the highest discharges are recorded associated with the high sediment transport from the glacier basins. During this time, suspended sediment concentration is hundred times higher than that at close of ablation period in October. This type of the behaviour is due to unique characteristics of glacier sediment delivery system, that is marked by spatial instability and sudden flood events (Jokulhlaups). It result in the transport of large quantities of sediment during a very short period (Ostrem et al., 1967, 75; Gurnell et al., 1982, Gurnell and Fenn, 1985; Collins 1979, 89, 91; Habreli, 1983). There are very low suspended sediment concentrations in streams after the peak sediment concentration with exceptionally high flow because of outbursting of subglacial channels and exhaustion of material in the channel (Collins, 1989, 1990).
The ablation period in the Indian Himalaya coincides with monsoonal precipitation (Hasnain, 1996) and controls the hydrologic regime in Himalayan upland streams and carries about 70-85 percent of their flow during this time (Bruijinzeel, 1989). The complex effect of monsoonal precipitation on the sediment transport in glacier stream is studied by Hasnain et al. (1999) and has been shown that 52% of the sediment transport occurs during early monsoon. During monsoon period (June-August), the stream accounts for 64% of the total discharge, 70% of the total suspended material transport and 74% of the monsoon precipitation. It indicates that the regional climatic conditions are clearly important in influencing energy availability for melting, the length of monsoon, the quantity of precipitation and influence the timing and amount of sediment delivered from the glacier basin.

2.12 Chemical characteristics of glaciers meltwater in Ganga Headwater

The pH and total dissolved solids in Himalayan glacier meltwater are significantly higher than in the meltwater from the glaciers of Northern Cascade Mountain (Ahmad, 1998). The meltwater streams from Nine Alaskan valley glaciers show a basic pH with low TDS than the high TDS and pH in Himalayan glaciers meltwater. It implies that the pH is dependent on the bed rock type and the weathering rate; higher the dissolution of bedrock, higher will be the pH and TDS of the meltwater (Meybeck, 1981). The percentage of various anions and cations in the meltwater of various Ganga headwater glaciers is given in Table-2.4. The anions type in glaciers meltwater show the abundance order of anions as \( \text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^- \). However, some glaciers such as Gangotri glacier and Bagni glacier meltwater belong to \( \text{SO}_4^{2-} > \text{HCO}_3^- > \text{Cl}^- \) type. The cations in the meltwater samples of Bagni, Gangotri, and Dokriani glacier meltwater were in order as \( \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ > \text{Na}^+ \) and \( \text{Ca}^{2+} > \text{Mg}^{2+} = > \text{Na}^+ > \text{K}^+ \) type respectively. But in the Satopanth - Bhaghirathi meltwater glacier the abundance order was \( \text{Ca}^{2+} > \text{Na}^+ > \text{Mg}^{2+} > \text{K}^+ \). It show that the chemical loads in different Himalayan glacier meltwater are highly influenced by basement rock type of glacier (Keller and Reshman, 1963; Ahamd, 1999). The different chemicals concentration and composition of glacier meltwater signifies that intensive chemical weathering takes place beneath the glaciers (Raiswell and Thomas, 1984; Hasnain et al., 1989, 91, 93). It has been also concluded that the
Glaciated catchments undergo more intense chemical weathering than those, which do not contain glaciers (Reynolds and Johnsen, 1972; Collins, 1983). Regarding the chemical composition of material transported in the solution, Maybeck observed that 90% of the dissolved load in the fresh water system is generally made up of just five components (HCO$_3^-$, SO$_4^{2-}$, Ca$^{2+}$, Na$^+$, and SiO$_2$). Among these Ca$^{2+}$, Mg$^{2+}$, Na$^+$, HCO$_3^-$, SO$_4^{2-}$ represent dominant cations and anions in most fresh water system. Gorham (1961) in his survey of factors influencing supply of major ions to inland waters briefly described were ion exchange and sorption phenomena. Cation exchange appeared to be an essential mechanism in the explanation of dissolved cation content of meltwater in the frontal zone of glaciers, this was indicated by studies on the rate and characteristic of water enrichment (Lorrain and Souchez 1972; Lemmens and Roger, 1978; Hasnain, 1996, 98). The studies by above workers on Alpine and Himalayan glaciers concluded that the alkalies adsorbed on the surface of the suspended and bed sediments are exchanged with the hydrogen ions in the water. The supply of the H$^+$ ions in the water results from the contribution of atmospheric CO$_2$, carbonate dissolution and pyrite oxidation. This phenomenon was favored by the presence of fresh material with a high abundance of clayey particles and a lower cross section/wetted perimeter ratio.

Table 2.4: Average chemical composition of different glaciers meltwater in the Garhwal Himalaya, Ganga Headwater.

<table>
<thead>
<tr>
<th>Name of Glacier</th>
<th>EC</th>
<th>Ca$^{2+}$</th>
<th>Mg$^{2+}$</th>
<th>Na$^+$</th>
<th>K$^+$</th>
<th>HCO$_3^-$</th>
<th>SO$_4^{2-}$</th>
<th>Cl$^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satopanth-Bhagirth (Chauhan, 1995)</td>
<td>7.2</td>
<td>39.3</td>
<td>295</td>
<td>30.6</td>
<td>58.6</td>
<td>114</td>
<td>671</td>
<td>216</td>
</tr>
<tr>
<td>Gangotri (Raju, 1993)</td>
<td>7.1</td>
<td>72</td>
<td>330</td>
<td>113.4</td>
<td>88.5</td>
<td>156</td>
<td>741</td>
<td>1269</td>
</tr>
<tr>
<td>Bagni (Ahmad, 1995)</td>
<td>7.6</td>
<td>121.8</td>
<td>680</td>
<td>269.1</td>
<td>20.9</td>
<td>456</td>
<td>1557</td>
<td>1710</td>
</tr>
<tr>
<td>Dokriani (Hasnain, 1995)</td>
<td>6.9</td>
<td>48.2</td>
<td>271</td>
<td>100</td>
<td>64.4</td>
<td>116</td>
<td>625</td>
<td>406</td>
</tr>
<tr>
<td>Kafni (Panda, 1992)</td>
<td>7.2</td>
<td>89.2</td>
<td>587</td>
<td>165</td>
<td>65.4</td>
<td>31</td>
<td>832</td>
<td>76</td>
</tr>
<tr>
<td>Bhagnyu (Singh, 1991)</td>
<td>6.9</td>
<td>40.5</td>
<td>267</td>
<td>52</td>
<td>46.3</td>
<td>34</td>
<td>243</td>
<td>92</td>
</tr>
<tr>
<td>Pimdari (Pandey, 1999)</td>
<td>7.6</td>
<td>147.6</td>
<td>1306</td>
<td>493</td>
<td>28.2</td>
<td>72</td>
<td>220</td>
<td>791</td>
</tr>
</tbody>
</table>

Units: µeq/l$^1$, except EC(µS/cm$^1$) and pH
2.13 Chemical and physical denudation rates in the Ganga Headwater, Himalaya

High altitude Himalayan drainage systems show intense physical and chemical weathering. The studies by Singh and Hasnain (1998) showed that the Alaknanda and Bhagirathi rivers at Devprayag deliver 1.58 million tons and 0.74 million tons of chemical load per year into the Ganga. The chemical denudation rate is 134 tons/km\(^2\)/yr and 95 tons/km\(^2\)/yr respectively for the Alaknanda and Bhagirathi rivers. This is three times higher than the global average chemical denudation rate (36 tons/km\(^2\)/yr.). The studies carried out on the suspended sediment delivery rates in various glacier basins by Chauhan (1995), Hasnain et al (1999), Lanzhou Institute (1980) and Fukushima et al. (1987) has also shown 1219 tons/km\(^2\)/yr., 15751 tons/km\(^2\)/yr., 6086 tons/km\(^2\)/yr. and 2453 tons/km\(^2\)/yr. suspended sediment delivers rate from the different Himalayan glaciers respectively (Table- 6.8). In the Ganga headwater, the annual suspended sediment transport of Alaknanda and Bhagirati river is estimated 4.20 million tons and 1.45 million tons at Devprayag and the rate of sediment erosion of Alaknanda and Bhagirathi basin is 356 and 321 tons/km\(^2\)/yr. These values are very high than that of the world average (150 tons/km\(^2\)/yr.) and comparable to average erosion rate of Indian sub-continent (327 tons/km\(^2\)/yr.). Such high rate of physical and chemical denudation is due to high relief, heavy rainfall, glacial erosion and favourable lithology that contributes to the intense weathering in the Himalaya (Hasnain, 1996).