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The rapid changes in environment quality and imbalances in their natural environment have been exaggerated by global climate change due to recent year’s anthropogenic advances and endless exploitation of natural resources (Mayewski et al., 1986, Ives and Messerli, 1989, Hasnain et al. 1989, 1999, Nijampurkar et al., 1992, Schreier, 1994, Arnolt and Carmichael, 1995). This change also disturbs mountains region’s mass balance and hydrological processes. Water management of mountain has attracted the attention of mountain researches in recent past (Ahmad, 1989, Ahmad and Hasnain, 2001, Bhatt and Panday, 1989, Hasnain, 1996, Kulkarni, 2005, Singh and Jain, 2002). The current trend of research is to study the three principles of mountain chains of the world: Alps, Andes and Himalayas. However, the knowledge of the water bodies on the high Himalayan mountain is very limited, particularly in western Himalaya (Collins, 1983, Hasnain, 2001, Rawat and Rawat, 1994).

The major rivers system of the world originates in mountain regions. It has been reported that 80% of the fresh water supply on planet earth comes from mountains (Barry, 1998). Mountains covered about 20% of land area and inhabited by 10% of the world’s population. Hindu Kush-Himalaya (HKH) (including Himalaya, Hindu Kush and Karakoram) is the biggest mountain range on the Earth, and the third largest ice mass after the Arctic/Greenland and Antarctic region. Hindu Kush-Himalaya (HKH) covers 59X10^3 km^2 of glacierized area out of a world total area of mountain glaciers of 540X10^3 km^2 (Dyurgerov and Meier, 2005). HKH region is the most populated on Earth (about 50-60% of the world’s population), it is potentially one of the most critical part of the world while considering the social and economical impacts of glacier shrinkages (Barnett et al., 2005).

2.1 The Himalaya

The Himalaya is the largest mountain range (33X10^3 km^2) of the HKH region, it separated India along its north central and north eastern frontier from China (Tibet) and extended between latitude 26°20’ and 35°40’ N and longitudes 74°50’ and 95°40’ E (Lives and Messerli, 1989). Glaciers in the Indian Himalayas cover an area of 38X10^3 km^2 account for 17% of the mountain area as compared to 2.2% in the Swiss Alps (Agarwal and Narain, 1991). According to Vohara (1993), the Himalaya is the tallest water tower and largest store house of snow and ice, outside of polar region. It contains enormous
water reservoirs of perennial snow and ice at the highest elevation. At present it has been estimated that approximately 10 percent of the land surface and 7 percent of the oceans are covered by glaciers.

2.2 Fresh Water Resources in the Indian Himalayas

The demand for global fresh water has increased four-fold since 1940 due to the growing population, intensifying agriculture, increasing urbanization and industrialization. In the Indian subcontinent snow and glacier of the Hindu-Kush Himalayas provide up to 90% of the low land dry season flows of the Indus, Ganges and Brahmaputra rivers and their vast irrigation network. In India, average rainfall is 117 cm and volume of rain water is 3838 km$^3$ y$^{-1}$ (Chandra, 2003). It is huge quantity but its distribution time and space is erratic. In many regions of the world distribution of water in rivers is seasonal; runoff process occurs only in rainy seasons, rest of the year rivers remain dry. In this dry seasons mountain glacier is only source of water for river. Runoff generated from snow melt and glacier melt from Indian Himalaya is 5% of the total rain fall of the country (Upadhyay, 1995, Bahadur, 1988). It shows that snow and glacier melting is poor producer of fresh water but good distributors throughout the year. The annual water availability from the Himalayan region has listed below:

<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>Rain fall</td>
<td>470</td>
</tr>
</tbody>
</table>


Table 2.1: Annual water availability from the Himalayan region to India

The glacier temporarily delays the melt water runoff due to storage in glaciers and contributes essentially to the runoff during dry periods and makes the flow perennial. So, glacial runoff is essential to the regional water balance in the mountainous regions because glacier mass change is important to regional water supplies (Bezinge 1979; Fountain and Tangborn 1985). The co-efficient of variation of runoff as a function of the percentage of glacier cover of a catchments basin indicates the impact of glaciers on the runoff. This storage can reduce peak runoff during periods of intensive melt and rain.
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Alternatively, the stored water can be catastrophically released from hidden reservoirs in the interior of the glaciers. Study of the glacier ablation is crucial for the planning and management of the corresponding water supply.

In recent years Glacier Mass Balance studies in India are also gaining attentions in context to dealing with many small and large projects based on the Himalayan water reserves. A well set and maintained glacier mass balance network is having manifold benefit because it provides:

1. Information on the glacier behaviour on the studied site.
2. Information on the climate fluctuations on the studied site.
3. Results defining the most important climatic processes controlling glacier growth and shrinkage.
4. Data defining the hydrological impact of glaciers on local and regional stream flow.
5. A way to estimate the behaviour of the non-monitored glaciers in the region. Many of these other glaciers may be important but otherwise impossible to monitor.
6. Information on the glacial response to climate fluctuations on the local, regional or the global scale.
7. Ideal site to launch other intensive investigations of the glacial.

2.3 Mass Balance

Change in the mass of glacier in any rational unit is called mass balance. Mass balance is the balance between accumulation and ablation, and is very dependant on climate (Bennett et al., 2000). Mass balance is influenced by climate because the level of precipitation determines the accumulation and ablation level (high levels of precipitation, the majority falling as snow increases accumulation) and temperature, which determines the type and amount of precipitation, and also influences ablation rates (Pelto, 1996). Change in the length of the glacier measured from its starting point to the terminus where ablation exceeds ice advection by glacier flow. So glacier length changes the linked to change in mass balance. After a change in mass balance the length of glacier will start changing and finally reaches a new equilibrium, however this process is very slow. So, change in glacier length indicates an extremely clear and easily understood but it is indirect, filtered and delayed indicator of climate change. For fast detecting of climate change we try to determine
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volumetric change in glacier by different methods such as glaciological method, geodic method, hydrological method, stratigraphical method, flux-divergent method etc. One of them is glaciological method, which used in present study.

Glacier mass balance indicates the glacier health. Change in snout position, ELA (Equilibrium Line Altitude), AAR (Accumulation Area Ratio) etc. provides quantitative information about relative climatic changes. Glacier snout retreat and advances were systematically observed in various part of the world. The World Glacier Monitoring Services (WGMS) in Zurich, Switzerland is one of the main centres of glacier studies, where the glacier of the world is monitored and all information on glaciers is collected and distributed (Haeberli et al., 2002, Haeberli and Muller, 1988). Studies shown that most of the world glaciers, the mass balance is showing a negative trend, very few of them are showing positive trend.

2.4 Worldwide Scenario of Glacier Distribution

The world's total glacier area is 16.2X10^6 km^2 of which only 0.7X10^6 km^2 lies outside the polar region, being scattered in the major mountain ranges mountain glaciers extend from tropics to high latitude and their mass balances highly depend on regional climatic regime. On the basis of glacial climatic regime, the earth surface can be categorized into, low latitude, mid latitude and high latitude, and the glaciers existing in these belts show distinct mass balance characteristics. Based on the delimitations suggested by Kaser et al. (1996), these glaciers can further be classified on the basis of their regional climatic conditions. The outer tropics have one wet and one dry season. Due to oscillation of the Inter Tropical Convergence Zone (ITCZ), the outer tropics are characterised by tropical conditions during their humid season and by subtropical dry conditions during their dry season. However, they can be distinguished from the inner tropical conditions, which have more or less continuous precipitation. Towards the higher latitude, the outer tropics are adjoined by the subtropics, which in general get no humidity from the ITCZ or from frontal activities of the west wind circulation system from mid latitudes. These extremely dry conditions lead to a glacier regime, which is very dry. The schematic glacial regimes of the inner and outer tropics are compared to that of the mid latitude in Fig.2.1 (Kaser et al., 1996a). The seasonal variation in mass balance of the mid latitude and high latitude glacier suggest that the accumulation and ablation are mostly controlled by seasonal temperature. The ablation is a
constant phenomenon in mid and high latitudes and consequently the mass balance is controlled largely by accumulation. In the case of inner tropics, the accumulation and ablation processes are controlled by rainy season and thus there is no seasonal variation in the air temperature. In this regions the temperature and humidity is more or less constant throughout the year and the accumulation and ablation goes simultaneously. Such conditions can be expected on the Rwenzori Mountains, East Africa, Irian Jaya, New Guinea (Kaser et al., 1996a). Seasonal variation in accumulation and ablation processes of the outer tropical glacier is quite different from the inner tropic glacier. Mass balance and energy balance processes on outer tropical glacier were studied by Kaser et al., (1996 a) through analysis of ablation measurements from Cordillera Blanca glacier and by Wagnon et al. (1999) on the Zongo glacier in Bolivia. The results show that during wet period ablation and accumulation goes simultaneously, while during dry period the energy is consumed by sublimation and less available for melting.

Fig. 2.1 The tropics and their delimitations from a glaciological point of view and the distribution of the glacier areas by country (Kaser, 1995, and Kaser et al., 1996 a).
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In 1970s, tropical glaciers represented 5% of the world's mountain glaciers, covering a surface comparable to glaciers of the Alps. The glaciers are spread over three continents, Africa, America and Asia (Indonesia), but 99% are concentrated in the Andes, with 70% in Peru, 20% in Bolivia and the rest in Andes, Ecuador, Columbia and Venezuela. These glaciers are believed to play an important role as climatic indicators because they are sensitive to climatic variation due to their reduced size and react rapidly to climate fluctuations. The vertical mass balance profile of glaciers in different climate regime leads to distinctiveness of its own, which is a result of the complex impact of climate on glaciers (Kuhn, 1984, Oerlemans and Hoogendoon, 1989).

2.5 Worldwide Scenario of Glaciers Mass Balance

The World Global Monitoring Services (WGMS) in Zurich, Switzerland is at present the central point, from where the glacier of the world is monitored and all information on glaciers is collected and distributed (Haeberli et al., 2002, Haeberli and Muller, 1988).

The developed countries such as Switzerland, USA, Canada, Norway, Sweden, Iceland, Japan, Austria, France, Russia etc. have carried out mass balance studies in many glaciers since early nineteenth century. A large number of mass balance studies are done since the beginning of the century based on the statistical relations or positive degree day method (Kodakove, 1966, Dyurgenov and Popovnin, 1981, Tvede, 1982 and Chen and Funk, 1990) and by use of remote sensing data (Jaenicke et al., 2006, Luckman et al., 2003, Kaab, 2002, Fricker et al., 2000). Lots of work has been done on glacier surface energy balance (Hay and Fitzharris, 1988a, Braithwaite and Olesen, 1990a, Munro, 1990, Ishikawa et al., 1992, Hannah and Gergor, 1997). Mass balance studies of the world are showing a negative trend on a global scenario (fig.2.2).

Since 1990s, glacier areas in Rwenzori Mountains in Uganda have decreased by about 75%. The continent of Africa warmed by 0.5°C during the past century, and the five warmest years in Africa has all occurred since 1988 (Kaser, 1999). Mt. Kenya's largest glacier is going to disappear in coming decades and it has also been found that 92% of the Lewis Glacier, Kenya has melted in the past 100 years (Hastenrath, 1991).
82% of ice cover of Kilimanjaro Mountain, Tanzania has disappeared since 1912, with about one third melting in just the last dozen years due to less snowfall on the mountain during the rainy season decreases the surface reflectance, leading to higher rates of absorption of heat and increased ice melt. (OSU, 2001). In 1972, there were six glaciers in Venezuelan Andes, now only 2 remain, and scientists predict that two will also be going extinct in the coming 10 years. Glaciers in the mountains of Columbia, Ecuador and Peru show similar rapid rates of retreat. Temperature recorded in other regions of the Andes show a significant warming of about 0.33°C per decade since the mid 1970s (OSU, 2001). The retreating rate of the Qori Kalis glacier (Andes Mountain, Peru) was increasing 4.0m/year to 30.1m/year from 1978 to 1995 (Mosley-Thompson, 1997).

The glaciers in Patagonia, Argentina have shown recession by an average of 1.5km (approximately) over the last 13 years due to an increase in maximum, minimum, and average daily temperature of more than 1°C over the past century in southern Patagonia east of the Andes (Wessels et al., 2001). In Tien Shan Mountains of China, the glacial ice has reduced by one quarter in the past 45 years even after increased precipitation caused by
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higher ablation than accumulation, (Meier, 1998 and Jing et al., 2006). The glacier mass balance shows a clear periodicity, with positive and negative alternations of 7 and 15 years during the past several decades in Ürümqi glacier, Tien Shan, China (Han et al., 2006). 102 measured glaciers in the region Gangrigabu mountains, southeast Qinghai-Xizang (Tibetan) Plateau, China have all retreated between 1915 and 1980, and between 1980 and 2001, only 40% of the glaciers were advancing due to increase in precipitation (Liu et al. 2006). The temperature variation was related to the heavy snowfall that occurred on the northern Tibetan Plateau in winter 1997/98. (Yang et al., 2006). The Khumbu Glacier, Nepal Himalaya has thinned recently in the ablation area (Nakawo et al., 1998). UNEP report published that 1081 glaciers of Pamir-Altai (Kyrghyzstan) have been disappeared due to 0.5-1.5°C rise in temperature since the 1950s (UNEP, 2000). Ice core records from the Dasuopu glaciers, Tibet shows that the past decade and last 50 years have been the warmest year in the last 1000 years. Meteorological records for the Tibetan Plateau shows an increase of summer temperature by 0.16°C per decade while the winter temperatures increased by 0.32°C per decade during the years 1955 to 1996 (Thompson et al., 2000).

Mid latitude glaciers are also showing significant shrinkages. In the European Alps, the ice loss has been about 50% in the past century, and New Zealand glaciers have shrunk by about 26% since 1890. The average elevations for glaciers in the southern Alps, New Zealand have shifted upslope by more than 91.4m over the past century (Chinn, 1996). In the Caucasus Mountain of Russia, the volume of glacier ice has decreased by about 50% in a century (Dyurgerov and Meier, 1997). In Spain there were 27 glaciers in 1980, the number has now fallen to 13 (Martinez, 1998). Recent studies show a record glacial retreat, that has lead to the emergence of a frozen Stone Age Mummy from a melting glacier in the Oetztal Alps, Austria. It indicates that glacial ice is more reduced today than at any time during past 5000 years (Haeberli and Beniston, 1998). The Athabasca glacier (Canadian Rockies) has retreated one third of a mile (0.5 km) in the last 60 years and has thinned dramatically since the 1950s-60s. In British Columbia, the Wedgemont glacier has also retreated hundreds of meters since 1979, as the climate has warmed at a rate of 1.1°C per century, twice the global average. Although, heavy summer snowfalls have a large impact on the mass balance of mid-latitude glaciers, because they simultaneously add mass to the glacier and reduce the
amount of absorbed solar radiation in the ablation zone of the glacier the snow has melted (Oerlemans and Klok, 2004).

A study of sixty seven (67) glaciers shows that between the mid 1950s and 1990s the glaciers thinned by an average of about 0.5m per year (Arendt et al., 2002). Repeat measurements on 28 of those glaciers show that from the mid 1990s to 2000-2001 the rate of thinning has increased to nearly 1.8m per year. Alaska has experienced a rapid warming since the 1960s. Annual average temperature has warmed upto 1°C per decade over the last three decades, and winter warming has been as high as 2°C per decade (Arendt et al., 2002). Rapid thinning of the Greenland ice sheet in coastal areas, especially of outlet glaciers studies during the 1990 shows that the coastal land ice loss is attributed to a combination of warming driven factors (high snow accumulation rates feeding the outlet glaciers) and increased rates of melting at the bottom of glaciers due to ocean warming (Krabil et al., 2000). Surface mass balance of Greenland ice sheet shows Mean accumulation was 0.287 m a⁻¹ (Hanna et al., 2002) and the surface mass balance measurements on Kangerlussuaq, West Greenland show a linear increase of the specific mass balance, with a mass-balance gradient of 3.7×10⁻³ m m⁻¹ (Van et al., 2005).

Comparison of DGPS data and surface DEMs with data from the topographic mappings from 1936 oblique stereoscopic aerial photographs and from Mission Russe in 1899-1901 shows that the Hornbreen and Hambergbreen surfaces are about 60-100 m thinner today in the upper part than at the beginning of the 20th century (Palli et al., 2003). Historical observations and photographs show that subsequent slow retreat changed to rapid iceberg-calving retreat after 1935, and that the tidewater terminus had withdrawn about 3.3 km from the late-Holocene maximum by 1992 (Barclay et al., 2003). During the last 2.5 years, glacier Upsala Lago Argentino, southern Patagonia west terminus had a net advance of around 300 m (Skvarca et al., 2003). Accumulation and ablation rates over an Antarctic blue-ice area spanning the 14 year period 1988-2002 have increased during the period 1988-2002 (Sinisalo et al., 2003). Mass balance of Austrian glacier shows that it was before 1965 more negative, during 1965-81 more positive and since 1982 more negative. Periods of more positive mass balance are highly correlated to winter accumulation and only slightly correlated to summer temperature (Schoner et al., 2000).
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The permanent ice cover of nine lakes on Signey Island, Antarctica has decreased by about 45% since the 1950s. Average summer air temperature has warmed by 1°C (Quayle et al., 2002). Bottom melting, appears to be a major source of mass loss on Antarctic ice shelves (Rignot, 2002). Large expanses of Tundra permafrost and Siberia are melting. In some regions, the rate of thawing of the upper ground is nearly 20 cm per year. Thawing permafrost has already damaged 300 buildings in the cities of Norilsk and Yakutsk. 1°C increase in temperature increased the rate of retreat by more than 5 times between 1933 and 1946 in Rabots Glacial, Sweden, (Brugger et al., 2005). For the period 1918-91 the specific mass-balance rate has been follow the decreasing trend at southern and northern slopes of Myrdalsjökull, ice caps, Iceland (Brandt et al., 2005). The Norwegian glaciers have all retreated during the 20th century and advances were recorded only around 1910, 1930, 1970 and around 1990 (Andreassen et al., 2005). The results of Queen Elizabeth Islands, Nunavut, Canada show continuing negative balances. All the glaciers and ice caps except Meighen Ice Cap show weak but significant trends with time towards increasingly negative balances (Koerner, 2005). Meighen Ice Cap may owe its lack of a trend to a cooling feedback from the increasingly open Arctic Ocean nearby (Johannesson et al., 1997). Results of Simple Dome, West Antarctica indicate that there is virtually no net thickness change probably due to recent retreat of the grounding line of ice stream (Hamilton, 2002). On average, the scale of glacier shrinkage is much smaller in continental Siberia than in central Asia and along the Pacific margins (Solomina, 2000). During the last five decades, a retreat of the glacier front by 1 km since 1956 due to climate warming by 1.4°C on the South Shetland Islands, while a neighbouring unnamed glacier advanced by 0.6 km and the northern ice-cap margin on King George Island was approximately stationary. (Macheret and Moskalevsky, 1999). Braithwaite’s (2002) analysis reveals “there are several regions with highly negative mass balances in agreement with a public perception of ‘the glaciers are melting,’ but there are also regions with positive balances.” Within Europe, for example, he notes that "Alpine glaciers are generally shrinking, Scandinavian glaciers are growing, and glaciers in the Caucasus are close to equilibrium for 1980-95."
### Review of Literature

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Name of the glacier</th>
<th>Country</th>
<th>Period</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>White glacier</td>
<td>Canada</td>
<td>1960 - 1991</td>
</tr>
<tr>
<td>2</td>
<td>Rhonegletscher glacier</td>
<td>Switzerland</td>
<td>100 yrs</td>
</tr>
<tr>
<td>3</td>
<td>South Cascade glacier</td>
<td>Washington</td>
<td>1967 - 1996</td>
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<tr>
<td>4</td>
<td>Aftotbreen</td>
<td>South Norway</td>
<td>1961 - 1990</td>
</tr>
<tr>
<td>5</td>
<td>Nigardsbreen</td>
<td>South Norway</td>
<td>1961 - 1990</td>
</tr>
<tr>
<td>6</td>
<td>Nhellstugrobreen</td>
<td>South Norway</td>
<td>1961 - 1990</td>
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<tr>
<td>7</td>
<td>Jakobahavns</td>
<td>W. Greenland</td>
<td>40 yrs</td>
</tr>
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<td>9</td>
<td>Haut glacier</td>
<td>Switzerland</td>
<td>1970 - 1991</td>
</tr>
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<td>De Sarenes</td>
<td>France</td>
<td>1966 - 1991</td>
</tr>
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<td>Nepal</td>
<td>1974</td>
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<td>13</td>
<td>Ghiacciaio del Calderone</td>
<td>Italy</td>
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<td>Zongo</td>
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<td>21</td>
<td>Himalayan Glaciers</td>
<td>India</td>
<td>1961-2006</td>
</tr>
</tbody>
</table>

Source: Dobhal, (2001)

Table 2.2 Glacier Mass Balance studies on world wide Scenario

When results for the whole world are combined for this most recent period of time, Braithwaite (2002) notes "there is no obvious common or global trend of increasing glacier melts in recent years. Some worldwide glacier mass balance studies are given in table 2.2.

"One of the most important problems for mass balance glaciology, after more than 50 years of hard work, is the sad fact that many glacierised regions of the world remain unsampled or poorly sampled.” suggesting that we really know very little about the true state of balance of most of the world’s (Braithwaite and Zhang, 2000).

Avalanches have also a great impact on mass balance, increase of precipitation and temperature shows that avalanche hazard may decrease slightly in winter (mainly February) and more significantly in May/June (Martin et al, 2001). It has been determined that during the acceleration phase of the avalanche front the underlying snow cover is mostly eroded and there is no deposition of snow (Solvilla et al., 2001).
2.6 Glacier Distribution in the Himalaya

Himalayas being abode to some 10,000 small and large glaciers are situated in the tropical-sub tropical belt between 26°20' N and 35° 40'N latitude and between 74°50' E and 95° 40'E longitude (fig.2.3). The Himalaya and Trans Himalaya comprise about 50% area of all glaciers outside of the polar region (Vohra, 1996) and perennial snow and ice cover about 43,000km² (Vohra, 1993) on the Himalayas. The glaciers in this mountain belt are unique in their location than others of the world, as being nearest to Tropic of Cancer receives more heat than by Arctic and Antarctica or other temperate glacial belts. Therefore, the Himalaya provides a unique opportunity to study the mass balance and snout fluctuations of the mountain glacier, which can be modelled for the different kinds of climatic regimes. Himalayan glaciers are more sensitive to climate change than other mountain glaciers in the world. As a consequence to increase in atmospheric temperature during the last century, deglaciation processes in Himalayan glaciers have enhanced at an alarming rate and are continuously experiencing the negative mass balance across Himalayan arc. Investigation through expedition and mapping to Chhota Shigri, Patsio and Samudra Tapu glaciers in Chenab basin, Parbati glacier in Parbati basin and Shaune Garang glacier in Baspa basin (estimated for 466 glaciers) has shown an overall reduction in glacier area from 2077 sq. km in 1962 to 1628 sq. km at present, an overall deglaciation of 21% (Kulkarni et al., 2007). However, the number of glaciers has increased due to fragmentation. Mean area of glacial extent has reduced from 1.4 to 0.32 sq. km between the 1962 and 2001. Even the number of glaciers with higher areal extent has reduced and lower areal extent has increased during 1962-2001. This indicates that a combination of glacial fragmentation, higher retreat of small glaciers and climate change are influencing the sustainability of Himalayan glaciers (Kulkarni et al., 2007). Many other glaciers of Himalaya shown trend of retreating study done by different workers, such as glacial variations in Baspa basin using remote sensing techniques (Kulkarni and Alex, 2003), Glacial retreat in the Baspa basin (Kulkarni et al., 2002), Alarming retreat of Parbati glacier (Kulkarni et al., 2005), Snout fluctuation study of Chhota Shigri glacier (Dhobal et al., 1994), Mass balance studies of Dokriani glacier, Garhwal Himalaya (Dhobal and Gergon, 1996), Effect of global warming on snow ablation pattern in the Himalayas (Kulkarni et al., 2002).
The Himalaya is a large mountain system, influencing the interaction impacts related to climate, hydrology and environment. There are about 6000 glaciers enclosed in the Indian part and their distribution is controlled by the altitude, orientation, slope and climatic zone in which they fall. The Himalaya can be classified in three zones depending on the amount of monsoon precipitation and the snowfall they receive (Chandra, 2003). The well known classifications of the Himalaya are as follows:

1. Dominant monsoon precipitation areas of Eastern and Central Himalaya.
2. Equal to sub equal monsoon and winter precipitation including areas of Ganga basin, parts of Himachal Pradesh.
3. Dominant winter precipitation including areas of Ladakh, Spiti and Tibet

Studies conducted by Ageta and Pokhral (1999), conclude that approximately 80 percent of the mass balance inputs is contributed by the monsoonal precipitation in the Eastern Himalayas. But in the Central Himalaya, they have observed that the monsoonal
precipitation contributes about 15 percent of the mass balance influx, whereas the rest can be attributed to the westerly disturbances (Ageta et al., 2000). In Western Himalaya the mass balance characteristics are largely controlled by winter accumulation. In this region, 85 percent of the influx is through winter precipitation. Thus different standards have to be set for assessing the mass balance characteristics in the Himalayan glaciers.

2.7 Indian scenario of Glaciers mass balance

Although, the Himalaya is the largest mountain range of the HKH region, but its glaciers are very poorly sampled in the field. In one of the most recent global inventories show that only 8 glaciers in India were studied for mass balance at least and above than one year till 2004 (Dyurgerov and Meier, 2005). Dokriani glacier, Garhwal Himalaya, India was not included in that inventory while it has been studied for 6 years between 1992 and 2000 (Dobhal et al., 2005). WGMS (2001) reported that no long term mass balance measurements have been carried out; all are less than nine years even some of them are only for one year. Since 2000, condition of mass balance study in India become worse, no mass balance measurements has been reported since 2000 (Dyurgerov and Meier, 2005). By use of satellite imagery many scientist are working on glacier (Kulkarni et al., 2007) and now a days it becomes a suitable tool to obtain more frequent sampling of glacier. But ground measurements are still needed as a calibration and a validation, and because the seasonal and annual mass balances cannot be precisely measured from imaginary. Some times remote sensing studies even address the question of glacier mass balance over a few years (Berthier et al., 2007).

In Himalayan glaciers detailed mass balance study was started by G.S.I in 1974. Gara glacier in Himachal Pradesh was taken for detailed studies and Department of Science and Technology (DST, Govt. of India) launched an all India coordinated programme on Himalayan glacier in 1986. The data compiled from 1812 by Mayewski and Jeschaka (1979) on the glacier history of high Asia indicate a peak position of the glacier during the year 1850 and a general state of retreat from that time. The Pendari glacier in Kumaon region has retreated by over 2.6 km since 1958. The Garhwal himalayas have some of the longest glaciers such as Gangotri in which the snout has retreated by 1100m. Bara Shigri
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and Chhota Shigri glaciers of Himachal Pradesh have shrunk by 1 to 1.5 km since 1850. Studies in the Gara glacier during 1974-1975 shows a positive net balance of the order of 2.48x10^6 m^3 in terms of water equivalent (Raina and Singh, 1977). A glaciological study was initiated in 1979 by fixing 20 stakes (Kaul and Tirkey, 1979) on the north east facing Rulung glacier. The Rulung glacier was monitored at the end of ablation season 1979-1980 and 1980-1981 (Shrivastava et al., 1980) and found that the glacier experienced a negative balance of 0.06x10^6 m^3 and 0.14 x 10^6 m^3 (water equivalent) respectively. Shrivastva and Swaroop (1989) experienced that Dunagiri glacier shown an increasing trend of negative mass balance due to increase in the rate of net ablation rather than net accumulation since 1985. The results of the study, carried out by Dobhal et al., in 1995, shows that the total retreat of Chhota Shigri glacier from year 1962-1963 to 1984 is about 165 m, with an average retreat of 7.6 m/yr. During 1984-1986 the glacier retreat varied with average rate of 2.6 m/yr (Dobhal et al., 1995). For the years 1986-1989 the snout position measured by EDM survey from the stable reference point indicates a glacier retreat of about 7.5 m/yr (Dobhal et al., 1995). The total retreating of glacier snout since 1962-1963 to 1989 (26 yrs) is about 195 m with an average 7.5m/yr. Tipara bank glacier, Baspa basin, Himachal Himalaya experienced a negative balance of 0.605 m during 1987-1988 (Sangewar et al., 1996). Winter stream flow for the Baspa basin has increased 75% since 1966 and local winter temperatures have warmed, suggesting increased glacier melting in winter (Kaul, 1999). Study on Shaune Garang glacier, Himachal Himalaya during 1982-1989 shown negative specific balance between 0.27m to 0.85m except one budget year 1982-1983 showed a positive value of 0.02m (Sangewar and Singh, 1989). Glaciers in Western Himalayas are retreating at an average rate of 15m per year, consistent with the rapid warming recorded at Himalayan climate stations since the 1970s (Kaul, 1999).

Winter stream flow for the Baspa glacier basin, Western Himalaya has increased 75% since 1966 and local winter temperatures have warmed, suggesting increased glacier melting in winter (Kaul, 1999). In Central Himalaya, India since the mid 1970s the average air temperature measured at 49 stations has raised by 1°C, with high elevation sites warming the most. This is twice as fast as the 0.6°C average warming for the mid latitudinal Northern Hemisphere (20° to 40°N) over the same time period, and illustrates the high sensitivity of
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Mountain regions to climate change (Shrestha et al., 1999). The Dokriani, Bamak glacier retreated 20.1m in 1998 despite a severe winter and the Gangotri glacier is retreating at the rate of 29.9 m/yr (Shrestha et al., 1999). At this rate the scientists predict the loss of all central and eastern Himalayan glaciers by 2035. The Khumbu glacier, Eastern Himalaya popular climbing route to the summit Mt. Everest, has retreated over 5 km since 1953. The Himalayan region overall has warmed by about 1°C since the 1970s (Shrestha et al., 1999). As Himalayan glaciers are melting the glacial lakes are swelling up which may lead to a catastrophic flooding. Average glacial retreat in Bhutan is 30-40m per year. Temperature in the high Himalaya has risen by 1°C since the mid 1970s (ICIMOD, 2002).

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Worker</th>
<th>Name of the glacier</th>
<th>Location</th>
<th>Period of study</th>
<th>Cummu.Sp.Bn.(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>GSI</td>
<td>Gor – Garag</td>
<td>H.P</td>
<td>1977 – 1985</td>
<td>-3.3</td>
</tr>
<tr>
<td>3</td>
<td>GSI</td>
<td>Shaune Garang</td>
<td>H.P</td>
<td>1981 – 1990</td>
<td>-2.87</td>
</tr>
<tr>
<td>5</td>
<td>GSI</td>
<td>Cangme Khangpu</td>
<td>J&amp;K</td>
<td>1978 – 1987</td>
<td>-1.86</td>
</tr>
<tr>
<td>6</td>
<td>GSI</td>
<td>Rulung glacier</td>
<td>J&amp;K</td>
<td>1979 – 1981</td>
<td>-0.021</td>
</tr>
<tr>
<td>7</td>
<td>GSI</td>
<td>Tipra Bamak</td>
<td>Uttarakhand</td>
<td>1981 – 1988</td>
<td>-1.34</td>
</tr>
<tr>
<td>8</td>
<td>GSI</td>
<td>Dunagiri</td>
<td>Uttarakhand</td>
<td>1984 –1982</td>
<td>-6.26</td>
</tr>
<tr>
<td>9</td>
<td>WIHG</td>
<td>Chhota Shigri</td>
<td>H.P</td>
<td>1986 – 1989</td>
<td>-0.21</td>
</tr>
<tr>
<td>10</td>
<td>WIHG</td>
<td>Dokriani glacier</td>
<td>Uttarakhand</td>
<td>1992 onwards</td>
<td>-1.47</td>
</tr>
<tr>
<td>11</td>
<td>Jammu</td>
<td>Nardu glacier</td>
<td>H.P</td>
<td>1992 – 1996</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>JNU</td>
<td>Chhota Shigri glacier</td>
<td>H.P</td>
<td>2002-2006</td>
<td>-1.39</td>
</tr>
<tr>
<td>13</td>
<td>SAC</td>
<td>Parbati Glacier</td>
<td>H.P</td>
<td>2003-2007</td>
<td>-</td>
</tr>
</tbody>
</table>


Table 2.3 Mass- balance studies of Himalayan glaciers

The Himalayan region overall has warmed by about 1°C since the 1970s (Shrestha et. al., 1999). Studies on some Himalayan glaciers in India are given in table 2.3.

2.8 Mass Balance and Climate Change

The snout recession, shrinking and thinning of glaciers in the Himalaya are important indicators for global climate-change. This is due to the fact that high-altitude, low-latitude glaciers are more sensitive to small temperature changes than glaciers located at lower altitudes and higher latitudes (Kasser et al., 1996). The sensitivity of glacier body
under climate change depends upon glacier climatic regime. It varies in Himalaya, from cold arid to wet tropical conditions with seasonal alterations of dry and moist conditions in wide range of altitudes. Hence, change in glacier size varies with geographical location. In the tropical environment in Southern slope Himalayan region the glacier are more sensitive to climatic changes (Kasser et al., 1996, Ageta and Fujita, 1996). These changes are perhaps more significant in Himalayas than elsewhere and are expected to continue this century (Hasnain, 1999, Naito et al., 2000). For summer-accumulation-type glaciers such as Sofiyskiy glacier, the most important climate factor controlling the glacier's surface mass balance is mean summer temperature (Nakazawa and Fujita, 2006). Maritime glaciers with low annual temperature range have proportionally more accumulation than continental glaciers with high annual temperature range for a similar summer mean temperature (Braithwite, 2006). Arctic island glaciers have low sensitivity to temperature changes consistent with their low mass-balance amplitude. However, very large changes in mass balance could occur on arctic island glaciers if the sea ice surrounding the arctic islands were reduced (Braithwaite, 2005). Winter precipitation in the form of snow is the major factor determining accumulation on Arctic glaciers (Grabiec, 2005). The mass balance of Engabreen is more sensitive to warming during summer than during winter, while precipitation changes affect almost exclusively the winter balance (Schuler et al., 2005). Shrinkage of the glaciers is linked with climate change due to decrease in winter precipitation increase in summer precipitation and atmospheric temperature (Singh and Kumar, 1997). According to IPCC (2001) report earth’s average temperature has increased by 0.6±0.2 °C in the 20th century and it may be rise by 1.4 °C to 5.8 °C by the end of 21st century. The projected trends will impact on the hydro-meteorological processes more vigorously than in 20th century. The impact of increased temperature and liquid precipitation on glacier and snowfield in the Himalaya will be profound (Barry 1998; Stone, 1992). Snowfields and glacier recession will impact on long-term, seasonal pattern and annual availability of fresh water and hydropower generating capacity (Johannessen, 1997, Bennet et al., 2000). The long-term water supply in the region is related to snow and ice storage in Himalaya and changes in size of glaciated area is critical for future sustainability under the present climate change scenario (Hasnain, 2001).

Glacier and snowfields in the Himalaya are the source of water in major River system in the Asia and supports a large population in mountain and adjacent areas. But rapid retreat
rate of mountain glaciers and dwindling snowfields world over since last thirty years threat the sustainability of water resources in near future. The rapid recession, mass wasting of glaciers and dwindling of snowfields are co-related with increase in Regional Thermal Anomaly (Oerlemans and Hoogendoorn, 1989; Oerlemans and Fortuin, 1989, Dyurgerov and Meier, 1997). The impact of increased temperature and precipitation on glacier and snowfield in the Himalaya will be profound, because snow and ice are more sensitive to atmospheric temperature (Barry 1990; Stone, 1992). These changes are, for long-term and may cause major economic disruptions. Enhanced melting is due to increase in global average temperature from 13.8 °C in 1950 to 14.6 °C in 1998 and summers becoming hotter. All the glaciers in the Himalayas are retreating at an average rate of 30 metres a year, compared with 18 metres a year between 1935 and 1999 (Kaul,1999). This enhanced melting of glaciers may lead to shrinking of Himalayan rivers in next 40 years. Though there will be an increase in river discharge at the beginning causing widespread flooding in the adjacent areas. But after few decades, this situation will get reversed and the water level in these rivers will start declining to a permanent decreased level.

The vulnerability of Himalayan glaciers is due to altitude range, variations in debris-cover, and summer air temperature. The glaciers located in central and eastern Himalayas are summer accumulation types nourished by the S-W monsoon. The summer mass balance equals the annual balance. During the last decades climate variability has enhanced air temperature in higher elevations, causing negative effects on glacier mass balance, as follows:

- Increased proportion of rain in the total precipitation reduces the accumulation by snowfall,
- Higher temperature increases ablation by sensible heat, and
- Decreased albedo due to decrease of snowfall and increases ablation by isolation.

In comparison to summer-accumulation type glaciers, most of which strongly depend on summer air temperature, variations of winter-accumulation type glaciers in the western Himalaya (Karakoram) depend on different combinations of much (little) snowfall in winter and high (low) air temperature in summer. If a combination of much (little) snow in winter and low (high) temperature in summer continues for several years, the tendency of glaciers to advance (retreat) becomes stronger.
2.9 Hydrochemistry of Glacial Meltwater

Geochemical and hydrological research has been carried out in various ecosystems to understand the factors controlling the chemistry of natural water (Likens et al., 1977; Brown and Bricker, 1990). To understand the processes controlling the hydrochemistry of Alpine and sub alpine system of America and Europe have been studied during last two decades (William et al., 1993, Psenner, 1989). Similar studies were also done in China and Central Asia (Xue and Schnoor, 1994). Ecosystem in Himalaya receives atmospheric precipitation for about 6-7 month in a year. Thus, atmospheric input represents a significant source of nutrient to the ecosystem (Reynolds and Johnson, 1972; Zeman, 1974; Gosz, 1980). Atmospheric input to the Himalayan uplands is mainly contributed by the southwest monsoon during summer, which is mostly dominated by high $\text{SO}_4$ concentration of anthropogenic origin from the Indian subcontinent (Wake et al., 1992). However during winter, westerlies bring snow and rain loaded with a usually high content of $\text{NO}_3$ from Central Asia and Europe (Wake, 1989). Nitrate and sulphate rich precipitation may result in water acidification and down water eutrophication (Galloway, 1989). Increased nitrate and sulphate concentration in the early meltwater fraction input into the stream can drop the pH of the stream to a harmful level for the aquatic life (Reuss and Johanson, 1986). The rapid snow melting processes and monsoonal rainfall over glaciers may effect the surface water chemistry in the Himalayan region very significantly.

Glacierised areas present an ideal environment in which to study water-rock interaction, since chemical weathering rates are high and anthropogenic impacts are often minimal (Brown, 2002). Water flow through glaciers exerts an important control on ice mass dynamics, and influences the quantity and quality of water delivered to environments downstream of glacierised basins. Thus, the study of the configuration and dynamics of subglacial drainage systems is important not only to enhance scientific understanding, but also to allow effective water resource utilisation in glacierised headwater catchments. Bulk meltwater quality characteristics draining terrestrial ice masses also offer the potential to provide unique information on hydrological and hydrochemical processes operating in the inaccessible subglacial environment. Here, significant advances have
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been made in understanding the controls on chemical weathering reactions, based on the identification of key dissolved indicator species. This has allowed water quality variations to be exploited as a tool for both subglacial hydrochemical and hydrological investigations. As a result, this area of glaciology has received considerable attention in recent years, utilising an increasing range of dissolved ions, and integrating field and laboratory studies. However, uncertainty still surrounds certain areas of meltwater quality science. A better understanding of the processes and rates of chemical weathering in glacierised environments has the potential to enhance our understanding of the environment, and to facilitate the exploitation of water quality variations for both scientific and applied uses. Glacier, the river of ice and snow is active agent of erosion and transport. Several studies proved that it has good capacity of chemical weathering. Studies on chemical characteristics of snow, ice and meltwater have been carried out in worldwide. Studies indicate that chemical weathering characteristics in Alpine environment is more intense in these regions (Lahaul Valley) than in tropics. (Hasnain et al., 1989). The chemical characteristics of meltwater discharge from glacier can be characterized by their chemical activity from the other aqueous environment. Geochemical analysis of meltwater near the snout shows enrichment in concentration of chemical species (Drewey, 1986). Presence of this concentration of chemical shows the effective hydrochemical reaction within the glacier system and particularly at the interface of the glacier bed rock. Above statement is also supported by (Reynolds and Johnson, 1972). Geochemical studies of meltwater in downstream 2km from snout indicate the active chemical weathering at low temperature (Reynolds and Johnson, 1972). Reynolds and Johnson (1972) explained that the silicate minerals are capable of reacting rapidly with water at near freezing temperatures. High dissolution capacity, of carbon dioxide in these cold waters enhances the supply of H+ ions needed for acid dissolved silica and clay minerals (Raiswell, 1984). Partial dissolution of suspended sediment may substantially contribute to the solute concentration (Collins, 1979). From the studies of Meybeck (1983) it is clear that the control of local geology on water chemistry is significant. He has reported that the water flowing over sedimentary rocks carries, comparatively, much higher dissolved load than those waters flowing over igneous rocks. The local geological variations may greatly affect the character of rivers,
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especially near their sources (Gorham 1961). Church (1972) has observed that high concentration of dissolved material derived from the subglacial conduits is mainly because of intense glaciation of the catchments.

Several authors reported diurnal variations in the chemistry of glacial melt waters (Singh et al., 2000b, 1995, 1997a and 2002, Hasnain et al, 1989, 1996). Rainwater and Guy (1961) and Collins (1979) suggested that this variation is mainly controlled by two component, one subglacial water and second supraglacial water. According to their observations the subglacial water gets enriched with dissolved solids because of long residence periods and contact with bed sediment. In other side, the supraglacial meltwater is fast flowing, dilute and its flow is directly controlled by heat flux. In this system concentrated subglacial water diluted by supraglacial water causes diurnal variation in the chemistry of glacial fed-streams.

Climate warming seems to be particularly pronounced in the Alpine region. A reduction of snow cover in space and time, due to less precipitation and higher temperatures, means a greater exposure of rocks and soils in the watersheds, which enhances weathering processes. A comparison between the two data sets shows an increase of solute contents in the last few years. This result could be attributed to increased weathering rates due to climate warming (Rogora et al., 2003)

2.9.1 Source of Solute Load in Meltwater

The solute loads in glacierized catchments mainly derive from two sources: atmospheric (wet and dry deposition or precipitation) and lithospheric (Collins, 1979). Solutes present in melt waters are derived from precipitation and also acquired during the passage of waters through the subglacial channels and ice-rock interface (Trudgil, 1986). Atmospheric contribution can be divided into two parts-wet precipitations and dry precipitation. Wet precipitations may be in the form of snow and rainfall dissolved with atmospheric gases and dry precipitation in the form of aerosols, snow fallout, radioactive fallout and dust storms. The atmospheric influences on water may be modified during storage and passage through snow and glacier. Lithospheric contribution may be divided into several parts but among them geology of the bed rock is dominant. When water drain through glacier internal conducts system, it approaches the bed rock the uptake of solute
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is rapid and chemical enrichment take place by process of ion exchange. Turbulent nature due to high velocity during draining and low temperature accelerates dissolution of the CO\textsubscript{2} in meltwater. This is responsible for the formation of weak acid which is important for exchange reaction between rock and water.

In the Chhota Shigri catchment, there is no land surface drainage except the glacier drainage system from over the glacier (Hasnain, 1989) and land surface penetrates the ice body and forms complete subglacial drainage. The lithological variation in the Rohtang Gneiss (base of the glacier) contributes in the type and amount of solute generation. Therefore, the solute load reflects the mixing of waters with different chemical composition from different lithologic environments. Various studies on Alpine glaciers, Rainwater and Guy (1961), Collins (1977, 1979a, 1979b), Behrens et al., (1971, 1975) and Elliston (1973), Lemmens and Roger, (1978), Lorrain and Souchez (1972) and Raiswell (1984) have suggested a two component subdivision of total flow water passing through the subglacial channels having ground environment and meltwaters running off rapidly by englacial channels, without undergoing chemical change. Intense glacierization of catchments, however results in the increased concentration of dissolved material, derived both from the ground environment and from suspended sediments (Church, 1974). In a study on Alpine basin, Zeman and Slaymaker (1975) has distinguished between snowmelt, glacier ice melt and baseflow and Collins (1978), in a similar studies have also quantified the proportion of subglacial and glacial water in a total discharge. However the investigations by Lorrain and Souchez (1972), Slatt (1922) and Church (1974), indicate that suspended load play an important source of solute draining from glacierized catchments.

2.9.2 Source of Dissolved Ions in Meltwater of Alpine Zone

The weathering of rock forming minerals, with minor contributions from cyclic sea salt and pollution, is the major source of ions in river water (Berner & Berner, 1987). Thus the chemical composition in terms of dissolved major ions can be explained on the basis of weathering of various rocks of the drainage basin. The chemical composition of glacial meltwater demonstrates that chemical weathering takes place beneath the glacier (Reynold & Johnson, 1972, Raiswell, 1984) and glaciated catchments undergo more intense weathering than catchments which don't have a glacier (Reynold and Johnson,
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1972, Collins, 1979). The two major anions HCO$_3$ and SO$_4$ in surface water are mainly derived from the dissolution of atmospheric CO$_2$ in water and the oxidation of sulfides (Garrels and Mackenzie, 1971). These two reactions provide the bulk of the protons which chemically weather carbonates, silicates and alumino-silicates in the drainage basin.

The dissolution of carbonate rocks proceeds more rapidly than silicate breakdown and is the likely mechanism of solute acquisition. The quantification of solution products of silicate weathering is difficult because of the incongruent dissolution (Sarin et al., 1992). The relative proportions of various ions in solution depend on their relative abundance in the host rock and on their solubility.

The data available on the geochemistry of meltwater shows that the apparent rate of denudation in glacierized basin in highly significant. Renolds and Johnson (1972) put forward a figure of 930 meq/m$^2$/a for the South Cascade glacier, Eyles et al. (1982), from their study have given a figure of 947 meq m$^2$ a$^{-1}$ for the Berendon glacier, Collins (1983) gave a figure of 478.1 meq m$^2$ a$^{-1}$ for the Gornergletscher. Hasnain (1992) in his study on the Chhota Shigri glacier in the Lahul Valley in the Himachal Pradesh Himalayas has calculated the average cationic denudation rate to be 24.86 mg m$^{-2}$ d$^{-1}$ for the ablation period in 1987 and 11.41 mg m$^{-2}$ d$^{-1}$ for the ablation period in 1988. The ongoing interaction of the Indian and Eurasian plate’s mountain uplift and high elevations ensure high level of precipitation and large glaciers, and steep unstable slopes maintain sediment supply to the rivers of the subcontinent (Collins and Hasnain, 1994). Increase runoff during the summer monsoon rains has been transferring sediments into the streams and causing floods (Ives and Messerli, 1989). In the high mountain regions, glaciers rub the mountain slopes and transport rock and boulders to the lower valleys. The water runoff caused by monsoon precipitation and glacier meltwaters contribute to rapid runoff and natural erosion (Regier, 1981).

2.9.3 The Process Which Controls Chemistry of Melting Water in Alpine Catchments.

The studies on the chemistry of meltwater emerging from the glacier 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,
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2.9.3.1 Chemical Weathering - Temperate glacial environment represents on extreme of hydrological condition, it may, therefore, represent an extreme of chemical weathering activity even in the absence of normal biological and pedogenic processes associated with the soil (Reynolds and Johnson, 1972). Evidently the low average temperatures generally associated with an active glacier don't inhibit chemical weathering reactions. The flowing water plays an important role in the dissolution and evaluation of minerals from glacierized catchments. Fenn 1987 proposed following mechanisms by which minerals are converted into ionic species.

1) Solution - Dissociation and evacuation of soluble ions from mineral (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 residue) produced by reaction between the mineral and the carbonate and bicarbonate ions contribute to water by the absorption of atmospheric CO₂

4) Hydration - Adsorption 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 condition, resulting is a change in susceptibility of decomposition.
Cation exchange - One to one interchange of cations between a water film rich in one cation and a mineral reach in other cation.

Reynolds and Johnson (1972) from their work in the Cascade Mountain concluded that, carbonation was 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 CO₂ reacts with water to form weak carbonic acid (H₂CO₃). Carbonic acid is unstable and soon breaks down to give H⁺ and HCO₃⁻ ions. Thus, the H⁺ ions released in this process react with the silicate minerals and in the process release the cations, dissolved silica and clay minerals to the water. 

\[
\text{H}_2\text{O} + \text{CO}_2 = \text{H}_2\text{CO}_3
\]

\[
\text{H}_2\text{CO}_3 = \text{H}^+ + \text{HCO}_3^-
\]

The carbonic acid reacts with carbonate and silicate produce bicarbonate.

\[
\text{CaCO}_3 + \text{H}_2\text{CO}_3 = \text{Ca}^{2+} + 2\text{HCO}_3^-
\]

\[
\text{CaMg(CO}_3)_2 + 2\text{H}_2\text{O} = \text{Ca}^{2+} + \text{Mg}^{2+} + 4\text{HCO}_3^-
\]

Primary silicate (Feldspar) + H₂O+CO₂ = Clay Kaolinite + cation +silica + HCO₃⁻

The low temperatures and the turbulent nature of the meltwater stream provide ample opportunity for continuous re-saturation of water with CO₂. The increased solubility of CO₂ in cold waters indicates that carbonation reactions will proceed more vigorously in colder regions than under moderate environmental conditions. Sulfide mineral 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 O₂ in turbulent and well-aerated water in Alpine environments promotes the oxidation reaction by constantly exposing the fresh rock surface to the water.

**9.3.2 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 is the explanation of dissolved cation content of meltwater 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 form their
work an Alpine glacier that alkaline 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 clay particles having larger surface area and the longer time of contact between water and morainic material. The rate of exchange is dependent on the greatest between the guoy layer and concentration of cations is water and also on the cations involved, for example, K⁺ defuses more quickly than Na⁺ and that Mg²⁺ 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. The surface of the mineral may be physically altered during surface ion exchange, rendering, it difficult to replace (or exchange) the adsorbed protons for dissolved base cations. 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 of dissolved CO₂ (Tranter et al., 1991).

9.3.3 Melting due to Pressure

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, 1987, Souchez and Lorrain, 1978, Hallet et al., 1978, Hallet, 1976a and b, Souchez et al., 1990). Formation of this basal ice layer at the sole of temperature 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 recrystalization on the lee side releases heat to the surrounding. Because of the pressure gradient the melt water move to the lee side of the obstacle, where relegation takes place at reduced pressures and higher temp.

During relegation the freezing ice will repeal the dissolve constituents, so that the remaining water gets enriched with solutes. When this water reaches over-saturation the excess gets precipitated. Widespread deposits of calcite precipitated over the till vacated by glaciers were reported by Hallet et al. (1978) from an area around Costleguard 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. To get precipitated, the water should get over saturated with the required component and in case of silica it reaches over saturation 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 concentration is higher than saturation point is these waters (Hallet, 1976). Keller and Reesman (1963) have reported as high as 8mg/l of dissolve silica concentration in Emmens and Nisquilly glacial milk, Mt. Rainier, USA. In the Canadian, Arctic, Apollonio (1973) reported greater dissolve silica concentration in a glacierised Fjord (Hasnain, 1989) than an unglaciated zone.

9.3.4 Leaching from ice

The study on ice indicates that the concentration of dissolved species decreases with depth (Brimblishecombe et al. 1986, Tranter et al. 1986, Reynold et al. 1978). According to Bourad (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 take 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 metal 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 dissolve solids with depth. So, older the ice less will be the concentration because of more and more leaching. However, (Gorham, 1961) has reported no leaching in the ice with depth. Harrison and Raymond (1976) attributed the concentration profile observed in the study of ice from Blue Glacier, Washington, USA to increase pollution levels. However studies on snow indicate that the concentration increases with depth. This may be causes by leaching of ions in to older snow during freeze-thaw cycles (Colbeck, 1981).

9.3.5 Drainage in Glacier

Drainage in glacier is like in channels system - water is conducted through glacier in three types of channels -viz., supraglacial (on the surface of glacier), englacial (within the body of glacier), and subglacial (below the glacier at the ice-rock interface). Shreve
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(1972) compared these channels with the channel network in the karts region. Collins (1979) envisaged two principal drainage route ways 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 of 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 (Rothlisberger, 1972)

9.3.6 Flow Rate of Water

Flow rate of water is also a factor to control chemistry of melting water. Considering the equilibrium constants of silicate and aluminosilicate weathering reactions can assess the influence of water flow rate or solute acquisition. 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.

9.3.7 Glacial Melts Water

Glaciers produce huge amounts of fine-grained sediment by mechanical erosion. The major source of suspended sediment of the melt water influence by glacial melt water 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 mater 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 networks, the fluctuation in significance to different sediment source areas, and routing of
sediment through the stream network (Gurnell, 1982). Higher flows will also flush out 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 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 et al. (1982) found that release of silica from suspended glacial rock floor in important mechanism acting in water of glaciated basin. Suspended sediment is an important source of solutes in water draining from active glacier (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 in exchange (Lemmens and Roger, 1978).

9.3.8 Physical Weathering

In glaciers catchments, physical weathering processes have long recognized as important in the production of sediments in huge quantity. Embleton and King (1975) have observed a five-fold difference in sediment yield between the glacierised Hoffelsjokull river in Iceland and a nearby non-glacier fed river. Number of studies has 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 basin with are ranging from 350 to10,000 km²), Janson (1998) found that within particular climate 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 presence of highly unsorted deposits found in the areas vacated by the glaciers is an indication to the potential of glaciers in the production of the sediment. Plucking, crushing, shearing and abrasion are the physical weathering processes in the Alpine basin. It found that along the sides and base in the Alpine basin erosion and most depositions occur (Embleton and King, 1975). Refreezing of water in the low-pressure areas at the sole of the glacier causes entrapment of debris in the ice layer. The glacier carries down incorporated debris and it acts more or less like sandpaper (Souchez and Tison, 1981). The debris carried by the sole of the glacier
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abrades the bedrock and moronic material at the bottom and sides of the glacier and produces fine sediments. This partly substantiates (Embleton and King, 1975), the finding that sediment yield form beneath ice sheet in Alpine areas are lower than yield for temperate glaciers, since the cold in the Arctic allows for little runoff to flush sediments from the glacier.

Studies on Higher Himalayan are very limited as compared to studied in other region. Whatever information has been documented so far, is not adequate to bring forth the entire hydrogeochemical, hydrological scenario of glacier meltwater. Hence there is need of more studies to be carried out, in order to provide base line data of hydrochemical, hydrological processes and weathering phenomena. This present studies would be helpful to understand the hydrochemical and hydrological processes in this region of Chhota Shigri glacier and will supplement the work carried out in the other parts of Himalaya.

Chhota Shigri glacier, Lahaul and Spiti district, Himachal Pradesh, India has been selected for mass balance as well as snow, ice and meltwater studies because of several reasons, such as:
1. Easy to access
2. Location, size and weather condition of the glacier
3. More data available

Chhota Shigri glacier is easy to access because it is only 100 km from Manali by road and even snout of this glacier is only 2.5 km from Chhota Dara road. Geographically this glacier located between 32°11' - 32°17' N and 77°29' - 77°33' E that lies on the Chandra river basin on the northern ridge of Pir Panjal range in the Lahaul- spiti valley of Himachal Pradesh. The total area of this glacier is 15.7 km² and catchments of this glacier is 34.7 km² (Wagnon et al., 2007). The climatic condition of this glacier is very interesting, it influenced twice in a year alternatively by Asian Monsoon in summer and mid-latitude westerlies in winter. So it has two distinct accumulations in summer as well as winter. During 1986 to 1988 Multi Disciplinary Glacier Expedition organized by Wadia Institute of Himalayan Geology, sponsored by Department of Science & Technology (DST), Govt.
of India. During this expedition, the morphology, the bedrock topography, meteorological parameters, hydrogeochemical as well as the dynamics of this glacier have been surveyed during the summer months of 1986, 1987 and 1988 (Dobhal et al., 1995, Kumar and Dobhal, 1997, Vardhan and Singh, 1989, Kumar, 1999, Kulandaivelu et al, 1989, Hasnain et al., 1989). The actual annual precipitation of this region is more than 100-1500mm (Kumar, 1989). The maximum and minimum velocity of glacier surface 38m/y and 21m/y respectively (Kumar, 1989). The total retreat of the snout between 1963 and 1989 has been evaluated at about 195 m (mean retreat over these 26 years of 7.5 m yr⁻¹; (Dobhal et al., 1995) but a recent study (Kulkarni et al., 2007) reports an accelerated retreat since 1988 with a 800 m retreat of the glacier terminus between 1988 and 2003 (mean retreat over these 25 years of 32 m yr⁻¹). Attempts of mass balance measurements have been done in 1986-1988 (Dobhal et al., 1995, Nijampurkar and Rao, 1992, Kumar, 1999) but they are questionable because stakes were drilled into the ice up to 1.25 m depth only and only part of the accumulation area is taken into account in calculations.

In 2002, International workshop has been organized in Chhota Shigri glacier by the help of International Commission on Snow and Ice (ICSI)-UNESCO HKH-Friend program with objective of monitoring the mass balance of mountain glaciers with particular attention to low latitude characteristics and trained researchers (participant) for mass balance and hydrological point of view. This glacier was purposed as a bench mark glacier during that training workshop. There are few characters for bench mark glacier it is described in chapter 4. During the training period it has been discovered that this glacier has been divided in two parts by medial moraines, one originating from east side of the accumulation area and flowing on the right bank of the glacier, Part-A and the second one coming from the west side and flowing on the left bank of the glacier, part-B (UNESCO, 2003).

The above literature review indicate that very little work has been done on Chota shigri glacier to understand the ablation, accumulation processes and the hydro chemical characterization of snow, ice and melt waters. Keeping these in mind, the present study has been undertaken on Chota shigri glacier to find out if there any significant differences in ablation rates between part A and part B and concentration of cation and anion of surface snow and ice and melt waters over the study period.