STATUS REPORT ON CHHOTA SHIGRI GLACIER (HIMACHAL PRADESH)
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Himalayan Glaciology Technical Report No. 1

Science and Engineering Research Council
Department of Science & Technology
Government of India
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FOREWORD

Glaciers in the Indian Himalaya are the key indicators of regional climate change and water resource to the major rivers like Indus, Ganges and Brahmaputra. Glaciers also contribute to the regional hydrology towards the development and sustainability of downstream population and mountain ecosystems. The Chhota Shigri glacier is one of the ideal glaciers for long-term monitoring, as index or benchmark glacier, located in the Chandra river basin on the northern ridge of Pir Pinjal range east of Rothang Pass in the Lahul valley of the Himachal Pradesh.

Glaciological expeditions to the Chhota Shigri glacier are being undertaken since 1962 by the Geological Survey of India. However, multidisciplinary expeditions during 1985-88, 2003-07 and individual studies supported by the Department of Science and technology and other organizations could generate valuable database to understand the dynamics of this glacier. The present report synthesizes the various observational studies available from the Chhota Shigri Glacier on meteorological and morphological features, glacier dynamics, hydrology, etc using multi-dimensional observational techniques including field and laboratory based as well as remote sensing. Available observations by different organizations and methodologies on this glacier snout position, which is the simplest indicator of climatic fluctuations, indicate a retreating trend with varied magnitudes. Further, the annual mass balance, energy budget, paleo glaciation and other glaciological processes could not quantify the specific factors driving the retreat and advance of this glacier.

I am confident that the renewed interest in Glaciological research to quantify the impact of climate change and global warming has provided great opportunity to take up intensive observational and modeling studies to provide scientific basis for adoption and mitigation of the impact of climate change in particular sustaining the Himalayan ecosystem as part of national action plan on climate change. We are grateful to Prof AL. Ramanthan for preparing this synthesis report and the Chairman and members of the Expert Committee on 'Integrated Program on Dynamics of the Glaciers in the Himalaya' for conceptualization and guiding the preparation of this report. Also, thankful to Dr Rasik Ravindra, Shri C.V. Sangewar, Dr D. Srivastava, Shri D.R. Sikka, Dr Naveen Juyal and Dr P. Sanjeeva Rao for critical review of the manuscript.

(T RAMASAMI)
Preface

The lofty Himalayan ranges have some of the highest and biggest mountain glaciers in the world and constitute an important source of fresh water for north Indian perennial rivers and water reservoirs. In order to sustain the rich biodiversity in the Himalayan region and to avoid a water crisis looming over the nation owing to a changing climate, study of snow and glaciers is crucial for the effective management of the mountain water resources, to satisfy the growing demands of a rapidly developing nation.

Glaciological studies are multidisciplinary in nature and encompass geological, hydrological, meteorological, geophysical, remote sensing and modeling applications. Apart from helping us to unravel the past climate, understanding the dynamics of Himalayan glaciers have their applicability in the environmental appraisal and mitigation of hazards like avalanches, lake outbursts, etc. in high altitude regions of the Himalaya.

Recently glacier studies have attracted the attention of the scientific community and public at large and several budding researchers are desirous of pursuing glacier research. There is, however, a lack of readily available compilations that report on various aspects of research carried out on any particular glacier. The purpose of this document is to provide information related to Chhota Shigri glacier collected from multiple sources. It also strives to bridge the gap between research done in the past and the ongoing research in the Himalaya in general and Chhota Shigri in particular allowing the reader to make informed judgments and also to address problems that need scientific answers in this field of applied research. Glaciologists around the world can have a glimpse of various kinds of scientific work that has been carried out on this representative glacier and can in turn suggest areas and problems that need to be addressed in the future.

This document contains five sections encompassing major aspects of basic geographical and geological information, glacier dynamics, chemical and hydrological investigations, palynological and remote sensing aspects on Chhota Shigri glacier. Each section gives a vivid picture of various approaches and problems. The first chapter introduces Himalayan glaciers in general and Chhota Shigri Glacier in detail including the climate, geology, etc. while the second chapter deals with various aspects of glacier dynamics i.e. snout fluctuation, mass balance, surface velocity, energy balance, etc. on which significant research has been undertaken till date. The third chapter covers various aspects of snow, ice and meltwater chemistry as well as radio and stable isotopic investigations. Hydrological Investigations viz, discharge and sediment load of the meltwater stream forms the fourth chapter. The final chapter is a compilation of miscellaneous research including palynological, remote sensing, geophysical investigation and mineral prospecting.

This document is expected to be a useful reference on glacier research to researchers in universities, institutes, NGO’s and in public and government sectors. I hope that it is widely circulated and used by national and international researchers, students and policy makers.

AL. Ramanathan
Editor
Acknowledgement

The editor is grateful to Science and Engineering Research Council, Department of Science & Technology, Government of India, for having funded the compilation of this report for publication through a short-term grant. In particular, we would like to convey our sincere thanks to Dr. M. Prithviraj, Scientist ‘F’ and Dr P. Sanjeeva Rao, Scientist ‘G’ for their constant support and encouragement throughout this report compilation and publication.

Director, Wadia Institute of Himalayan Geology, Dehradun, Director, Glaciology Division, Geological Survey of India, Lucknow and Director, National Institute of Hydrology, Roorkee are acknowledged for granting access to their libraries for collecting material for publishing this document.

Late Dr. Surendar Kumar, Scientist, Wadia Institute of Himalayan Geology, Dehradun had co-ordinated the multidisciplinary Chhota Shigri Glacier Expeditions between 1986 and 1989, in which various institutions like Survey of India, Geological Survey of India, National Institute of Hydrology, Jawaharlal Nehru University, Physical Research Laboratory and Space Application Centre (ISRO), Defense Terrain Research Laboratory, etc. participated and generated a large volume of data in a short time.

Dr. D. P. Dobhal of WIHG, Dehradun, Dr. K. Dhanapal, Coimbatore gave access to their unpublished Ph.D. thesis and other material for this compilation. Several papers in reviewed journals and conference proceedings have also been accessed for this compilation.

We thank the various institutions and scientists who have studied Chhota Shigri glacier over the last 25 years either individually or as part of Scientific Expeditions. The authors are very grateful to the three referees viz. Dr. D.R. Sikka, Ex-Director, IITM, Dr. R.K. Midha, Ex-Advisor, DST, Dr. C.V. Sangewar, Ex-Director, Glaciology Division, GSI and Dr. Rasik Ravindra, Director NCAOR and Chairman, Expert committee on Dynamics of Himalayan Glaciers who painstakingly went through the draft report and gave their valuable inputs which have considerably improved the quality of this report.

Finally, I extend my hearty thanks to Dr. P.G. Jose, Dr. Parmanand Sharma, Dr. Anurag Linda, Dr. Shruti, Mr. Mohd. Farooq Azam and Mr. Virendra Bahadur Singh who helped in preparing this document.

AL. RAMANATHAN
Executive Summary

The majestic Himalaya with its snow clad peaks and over 9000 glaciers is a major source of fresh water for the Himalayan rivers and one of the largest reserves of snow and ice outside Polar Regions. The glaciers in Indian Himalaya are yet to be substantially explored for their resource and hazard potentials. Few glaciers in Indian Himalayas have been monitored for more than ten years. Chhota Shigri glacier is one of the representative glaciers that have been studied for a relatively longer period. The studies carried out so far in various disciplines on this glacier are not enough to come to a definite understanding of its health. Hence we need more comprehensive and long term monitoring to understand the glacier dynamics and its response to local and regional climate. This document aims to compile the work carried out in the form of a status report to highlight not only what has been accomplished, but also to inspire further discussion on what need to be done to better understand climate-glacier-bedrock interactions and the factors controlling these. The status report contains six sections encompassing major aspects of basic geographical and geological information, glacier dynamics, chemical and hydrological investigations as well as polynological, geological/geophysical and remote sensing investigations on Chhota Shigri glacier.

In chapter 1, basic information pertaining to Chhota Shigri glacier is discussed. Geographically, Chhota-Shigri glacier is located between 32° 11’-32° 17’ N and 77° 29’-77° 33’ E, in the Chandra river basin on the northern ridge of Pir Panjal range in the Lahaul- Spiti valley of Himachal Pradesh, India. The glacier catchment is dominated by gneiss, with traces of sulphites and deposits of stibnite. The glacier has clearly demarcated ablation and accumulation zones and various erosional and depositional glacier morphological features like moraines, crevasses, glacier till, cirques, glacier tables and glacier lakes etc. Climatic conditions around this glacier are typical of monsoon-arid transition zone, where both Asian summer monsoon and mid-latitude Westerlies influence the climate regime. The annual precipitation varies between 150 and 200cm. and wind velocities range from 5 to 15kmh⁻¹.

Chapter 2 deals with glacier dynamics i.e., snout fluctuation, mass balance, surface velocity and energy balance. The snout retreat of this glacier is well documented from 1962 onwards, although there is wide variability in retreat rates reported by different sources. Mass balance by Glaciological method also shows negative mass balance of about 0.2m water equivalent during 1986 to 1989 and about 1.0m water equivalent during 2002 to 2009 in this glacier. Equilibrium Line Altitude and Accumulation Area Ratio indicate the overall negative mass balance trend. Ice flow velocities on the glacier surface have remained relatively constant all through the observation period, with the mean annual surface velocity ranging from about 30 to 40myr⁻¹.

Chapter 3 deals with chemical investigations done on Chhota Shigri glacier and its melt-waters. Chemical investigation of melt-water shows that dominant cation in this basin is calcium followed by magnesium and dominant anion is bicarbonate followed by sulphate. It also indicates dominance of carbonate weathering over silicate weathering. The age of snout ice was calculated as 250 years while that of average meltwater as 80 years by analyzing radioisotopic composition, while stable isotopic analysis gave the rate of snow accumulation on this glacier to be 520 kgm⁻²yr⁻¹.

Chapter 4 deals with chemical investigations done on Chhota Shigri glacier and its melt-waters. Chemical investigation of melt-water shows that dominant cation in this basin is calcium followed by magnesium and dominant anion is bicarbonate followed by sulphate. It also indicates dominance of carbonate weathering over silicate weathering. The age of snout ice was calculated as 250 years while that of average meltwater as 80 years by analyzing radioisotopic composition, while stable isotopic analysis gave the rate of snow accumulation on this glacier to be 520 kgm⁻²yr⁻¹.

Glacier hydrology is the subject matter covered in Chapter 4, giving insight into discharge and sediment load in Chhota Shigri glacier melt-waters. Discharges measured intermittently show significant variation with daily mean discharges ranging from 6 to 13m³s⁻¹. Sediment load closely follows the discharge variations.
Chapter 5 deals with miscellaneous research not covered in the previous chapters, such as palynological, remote sensing and geophysical investigations as well as mineral prospecting studies on the moraines. Palynological studies revealed the influence of upthermic winds in the catchment. A good relationship was found between the satellite observations and the mass balances measured on the field. Geophysical investigations shed light into relation between maximum ice thickness and the maximum strain rate, surface ice velocity and melting rates as well as the bed rock topography and surface topography.

The monitoring of Chhota Shigri glacier was initiated through the multi-institutional expeditions during 1986-1989 sponsored by Department of Science and Technology, Government of India and renewed from 2002 through the annual mass balance monitoring of the glacier by researchers from Jawaharlal Nehru University, New Delhi through collaborative research. Mass balance of a glacier depends on various climatic factors like precipitation, mean summer temperature, insolation, albedo, etc. and physical factors like sliding rate, tectonism, etc. Thus there is a need to strengthen the ongoing research with inputs from various disciplines and involvement of specialists from diverse fields of research. A multi-disciplinary approach with participation from a broad spectrum of specializations like glaciological modeling, geochronology, isotope- and bio-geochemistry, geophysics, meteorology, hydrology, etc. apart from glaciology and glacial geology appears to be the key to further a holistic understanding of climate-glacier interactions not only in Chhota Shigri glacier but also in the Himalayan region.
List of Institutions involved in studies of Chhota Shigri Glacier

1. Birbal Sahni Institute of Palaeobotany, Lucknow
2. Central Water Commission, New Delhi
3. Defense Terrain Research Laboratory, Delhi
4. Geological Survey of India, Lucknow
5. India Meteorological Department, New Delhi
6. Institute of Geology & Mines, Shimla
7. Jawaharlal Nehru University, New Delhi
8. National Institute of Hydrology, Roorkee
9. Physical Research Laboratory, Ahmedabad
10. Space Application Centre, Ahmedabad
11. Survey of India, Dehradun
12. Wadia Institute of Himalayan Geology, Dehradun
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1. Introduction

The major river systems of the world originate in the mountainous regions. It has been reported that 80% of the fresh water supply on planet earth comes from mountains (Barry et al., 1998, Valdiya, 1998), which cover about 20% of land area and are inhabited by 10% of the world’s population. Hindu Kush-Himalaya (HKH) including Himalaya, Hindu Kush and Karakoram is the biggest mountain range on earth, and is the third largest ice mass after Arctic/Greenland and Antarctic regions. HKH covers $59 \times 10^3 \text{ km}^2$ of glaciated area out of a world total of $540 \times 10^3 \text{ km}^2$ (Dyurgerov and Meier, 1997, 2005) mountain glaciers. This region is one of the most populated areas on earth and is potentially one of the most critical parts of the world while considering the social and economical impacts of glacier shrinkages (Barnett et al., 2005).

1.1 Glacier

The word glacier comes from Latin glacies meaning ice. Meier (1964) defines glacier as “a body of ice originating on land by the re-crystallization of snow or other form of solid precipitation and showing evidence of past and present flow”. According to Knight (1999), glacier is “a huge mass of ice slowly flowing over a land mass, formed from compacted snow in an area where snow accumulation exceeds melting and sublimation”. Many authors define glacier as a large mass of ice which persists throughout the year, and moves slowly downslope by its own weight. Glaciers are formed in areas where the winter snow doesn't have a chance to melt, and consecutive snowfalls accumulate and compress into ice. A glacier forms where the mass accumulation of snow and ice exceeds ablation over many years. Glacier ice is the largest reservoir of fresh water on earth. Glaciers are categorised in many ways on the basis of their morphology, thermal characteristics and behaviour. There are two common types of glaciers: alpine or mountain glaciers and ice sheets or continental glaciers. Alpine glaciers, those confined to mountain valleys are also called valley glaciers, while continental glaciers cover large tracts of land greater than 50,000km$^2$ (Keller, 1999). Most of the Himalayan glaciers are valley type glaciers.

1.1.1 The Himalaya

The Himalaya is the largest mountain range of the HKH region. It separates India along its north central and north eastern frontier from China (Tibet) and extends between latitude $26^020'$ and $35^040'$ N and longitudes $74^050'$ and $95^040'$ E (Ives and Messerli, 1989). In Indian
Himalaya, about 1400 km$^3$ of snow and ice is locked up (Valdiya, 1998) and covers an area of 38x10$^3$km$^2$ accounting for 17% of the mountain area as compared to 2.2% in the Swiss Alps (Agarwal and Narain, 1991). A recent inventory compiled by the Geological Survey of India has revealed the existence of 9,575 glaciers in the Indian administered part of the Himalaya comprising the territories of Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh (Sangewar and Shukla, 2009). The total glacier cover within these states is 37.466 x 10$^3$km$^2$ (Raina and Srivastava, 2008). According to Vohra (1996), the Himalaya is the tallest water tower and largest store house of snow and ice outside the polar region. It contains enormous water reservoirs of perennial snow and ice at the highest elevations.

1.1.2 Fresh Water Resources in the Indian Himalaya

The global demand for fresh water has increased four-fold since 1940 due to growing population, intensifying agriculture, increasing urbanization and industrialization. In the Indian subcontinent, snow and glaciers of the Hindu-Kush Himalayas provide a major portion of the dry season flows of the Indus, Ganges and Brahmaputra rivers. There is a high variability in precipitation across the Himalaya and even different ranges in the North Western Himalaya receive different amounts of snowfall ranging from about 100 to >1600cm (Bhutiyani et al., 2009). In many regions of the world, the distribution of water in rivers is seasonal; runoff process occurs only in rainy seasons and rest of the year, rivers remain dry. In these dry seasons, mountain glaciers are the only source of water for rivers. Runoff generated from snow melt and glacier melt from Indian Himalaya is 5% of the total rainfall of the country (Upadhyay, 1995; Bahadur, 1988). This shows that snow and glacier melt are not major sources, but good distributors of fresh water throughout the year. The annual water availability from the Himalayan region is listed below (Table 1.1).

**Table 1.1 Annual water availability from Himalayan region to India (Upadhyay, 1995)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Volume of water (km$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glacier melt</td>
<td>40</td>
</tr>
<tr>
<td>Seasonal snow melt</td>
<td>160</td>
</tr>
<tr>
<td>Rain fall</td>
<td>470</td>
</tr>
</tbody>
</table>
Glaciers temporarily delay the melt water runoff due to internal storage and essentially contribute to the runoff during dry periods and make the flow perennial. Therefore 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 variation of coefficient of runoff as a function of the percentage of glacier cover of a catchment basin indicates the impact of glaciers on the runoff. This storage can reduce peak runoff during periods of intensive melt and rain. Alternatively, the stored water can be catastrophically released from hidden reservoirs of the glaciers. Hence, monitoring glacier ablation pattern is crucial for planning and management of water resources.

In recent years, glacier studies in India are gaining attention in the context of climate change and especially in view of the existing and upcoming small and large scale hydro-power/irrigation projects based on Himalayan water reserves. This has given an imperative to monitor representative glaciers from different hydroclimatic regimes across the Himalaya.

1.1.3 Glacier Distribution in the Himalaya

The Himalaya and Trans-Himalaya comprise about 50% area of all glaciers outside of the polar region (Vohra, 1996). The glaciers in this mountain belt are unique in their location, as being nearest to Tropic of Cancer they receive more heat than Arctic and Antarctic or other temperate glaciers (Figure 1.1). Therefore, the Himalaya provides a unique opportunity to study the mass balance and snout fluctuations of the mountain glaciers, which can be modelled for different kinds of climatic regimes. Investigations through expeditions 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 has reported an overall deglaciation of 21% from 1962 to 2001 (Kulkarni et al., 2007).
The Himalaya is a large mountain system, influencing the interaction of climate, hydrology and environment. There are 9575 glaciers enclosed (Sangewar and Shukla, 2009) in the Indian part of Himalaya and their distribution is controlled by 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. The well known classification of the Himalaya (Vohra, 1996) is 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% 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% 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% of the influx is through winter precipitation (Ageta et al., 2000).
This study is focussed particularly on the Chhota Shigri glacier, Lahaul-Spiti valley, Western Himalaya; representative of glaciers influenced by two major climatic systems i.e. the mid-latitude westerlies and the Indian South-West summer monsoon. This region is still poorly monitored due to difficulties in maintaining observational networks at high elevation. Chandra River, an important source of fresh water in this region is fed by various glaciers, one of which is Chhota Shigri glacier. Information available on mass balance, discharge and chemistry of snow, ice and meltwater of Chhota Shigri glacier is sparse and inadequate and needs to be substantiated by comprehensive scientific studies over the next few decades.

1.2 Chhota Shigri glacier

Chhota Shigri glacier is a valley-type compound glacier (GSI Inventory 2009: Identification No. IN5Q21212159). The flow direction of the trunk glacier is from south to north. The glacier is oriented roughly N-S in its ablation area, and has a variety of orientations in the accumulation area (Figure 1.2). The slope of the glacier in the lower region is about 10° to 16° and in the higher elevations (head of the glacier) the slope is about 40° to 45° (Kumar and Dobhal, 1997).

1.2.1 Location

Geographically Chhota Shigri glacier is located between 32° 11’ - 32° 17’ N and 77° 29’-77° 33’ E. It lies in the Chandra river basin on the northern ridge of Pir Panjal range in the Lahaul-Spiti valley of Himachal Pradesh, India. Table 1.2 gives a list of geographical and topographical characteristics of Chhota Shigri glacier (Wagnon et al., 2007; Sangewar and Shukla, 2009). Chhota Shigri glacier is fed by mainly two tributary glaciers from the east and west, both of which originate in the vicinity of peaks located at about 6000m and 5500m amsl. respectively. The location map of Chhota Shigri glacier is shown in Figure 1.2. To the east of Chhota Shigri is the largest glacier of Himachal Pradesh, Bara Shigri, a 28 km long and 131km² glacier (Dutt, 1961; Berthier et al., 2007; Sangewar and Shukla, 2009).

Chhota Shigri valley extends 11 km from the Chandra river confluence up to Sara - Umga Pass (4990m amsl) and the walled valley extends for 10 km. The lower 1km distance is over the terrace of main Chandra river valley covered on the sides by lateral moraines 50m high. The drainage area of the Chhota Shigri basin from the location of hydrological station on the proglacial stream at 3900m amsl is 34.7km², of which 47% is glaciated. The total glaciated area is 16.3km² while the Chhota Shigri glacier covers 15.7km² (Wagnon et al., 2007).
The main glacier is slightly crescentic with a westerly arch. It is fed by several tributary glaciers, which are mostly transverse to sub-transverse type. The accumulation zone near Sara Umga Pass is situated between two peaks of 5500m and 6500m amsl.

Table 1.2 Geographical and topographical characteristics of Chhota Shigri glacier

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Wagnon et al., 2007</th>
<th>Sangewar and Shukla, 2009</th>
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</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>32° 11’ N to 32° 17’N</td>
<td>32° 13’ 42” N</td>
</tr>
<tr>
<td>Longitude</td>
<td>77° 29’E to  77° 33’ E</td>
<td>77° 30'50” E</td>
</tr>
<tr>
<td>Max. Elevation</td>
<td>6263m amsl</td>
<td>6080 amsl</td>
</tr>
<tr>
<td>Snout position</td>
<td>4050m amsl</td>
<td>4060 amsl</td>
</tr>
<tr>
<td>Chhota Shigri glacier area</td>
<td>15.7km²</td>
<td>15.01 km²</td>
</tr>
<tr>
<td>Glacier length</td>
<td>9km</td>
<td>9.20km</td>
</tr>
<tr>
<td>Mean orientation</td>
<td>North</td>
<td>NW/N</td>
</tr>
</tbody>
</table>

The Chandra River valley is 8km wide at the top and 2km wide at the valley floor, while Chhota Shigri valley varies from 0.5km near the snout to 2-3km at the accumulation zone (Sharma, 2007). Constant fall of boulders and cobbles were observed all around the snout region. The total length of glacier is 9km from snout to Sara Umga Pass. The present snout is about 2.5km south of Chhota Dara. The Chhota Shigri glacier stream flows in a NW direction and meets the Chandra River at right angle at about 2.5km downstream of the snout. The Chandra River flows in E to W direction at the confluence.
c)  

Source: NASA World Wind 1.4

Figure 1.2 (a, b and c) Location map of Chhota Shigri glacier.
1.2.2 Glacier Geometry and Morphology

Chhota Shigri Glacier extends for about 9km (Kumar, 1991) from its snout to the accumulation zone near Sara U mga Pass (4990m). The glacier is fed by converging mountain glacier tributaries originating on the slopes of peaks that range in height from about 5500m to 6500m amsl (Dobhal et al., 1995). The average bed slope of the valley is about 12.5° (Dobhal et al., 1995). The main glacier flows in a NW direction for about 4km in the accumulation zone and then changes the direction to NNE near the equilibrium line. The lowermost part of the glacier tongue for about 1km is covered by supraglacial moraines. The glacial surface is uplifted by medial moraine which is depressed near the snout. This glacier lies on the northern slopes of the main Pir Panjal Range east of Rohtang Pass, resting mainly on Central Crystalline granites.

The diverse morphology of the glacier surface and its catchment area may strongly reflect the impact of causative agents such as high temperature range in the development of these specific geomorphological features during the mechanical weathering process under the extreme range of temperature. This glacier reflects the remnants of a pre-glacial river valley deepened by glacial or meltwater erosion (Chaujar, 1987). These weathered materials get carried away to the downstream region with the melt water and get deposited as the debris cover. A preliminary level investigation was conducted in the ablation seasons of 1986, 1987, 1988 and 1989 to study the morphology (Figure. 1.3) and glacier dynamics of Chhota Shigri glacier (Chaujar, 1987, 1989, Dobhal et. al., 1995). Detailed topographic survey of the glacier was carried out by SOI in 1986 assisted by scientists from WIHG and a high resolution topographic map (1: 10,000) was prepared (Kumar et al., 1987). A resurvey of the glacier topography at 1:10,000 scale is an immediate need to update the current areal extent of the glacier and to understand prevailing glacier geometry.

Initially Chaujar (1987) classified this glacier into two fold, a) Active Zone-Landforms produced by contemporary glacial processes b) Inactive Zone-Landforms in relict state due to glacial recession. Active zone is further divided into two zones viz.(a) the ablation zone and (b) the accumulation zone. Landforms in the active zone are moraines, crevasses, glacier till, cirques, glacier tables and glacier lakes. Landforms in the inactive zone are lateral, ground and end moraines.
Figure 1.3 Geomorphological features of Chhota Shigri glacier
(Chaujar, 1989; Dobhal, 1992)
Based on various field expeditions carried out in this glacier valley, well-developed morphologic zones were identified like accumulation zone, ablation zone, snout, etc. The accumulation zone enclosed by high peaks forms an elongated cirque. The upper part of the zone is slightly steep. The glacier coming down from the upper reaches is dislodging the load on the western side of the glacier, hence resulting in a smooth but large bend in the glacier valley around the equilibrium line (Dobhal et al, 1995). The maximum crevasse formations around the equilibrium line zone are long and wide, mainly transverse-type oriented almost in east to west direction, suggesting bedrock control when the slope break. The slope increases gradually and becomes steep in the lower part of the ablation along with narrowing of the valley (Dobhal et al, 1995). Approx. 1km of lower part of ablation zone including snout is covered by debris. Several glaciogenic features are developed like lateral moraines on both sides, supramoraines, glacier tills, glacier tables, ice pillars, moulins, crevasses and mud flow, etc. (Chaujar, 1987, Dobhal et al, 1995). The snout (Figure 1.3, 1.7) of the glacier at a height of 4050m amsl (approx.) is situated about 2.5km south of the Chandra River opposite Chhota Dara (Dobhal et al., 1995). The first record of snout position available for the glacier front is from the Survey of India toposheet No. 53H/11 (1962-1963) on 1: 50,000 scale.

A geomorphological map (Figure. 1.3) of the Chhota Shigri glacier has been prepared on the scale of 1: 10,000 (Chaujar, 1987; Dobhal et al., 1995). The slope morphometry of the Chhota Shigri catchment as well as of the glacier valley shows that most of the morphological features are developed due to mechanical weathering related to intense variation of temperature. The weathered products have been carried down by either the melt-water or as mass flux. The prominent features include snow-clad peaks, cirques, truncated spurs with snow-off faces, hanging valley, conical and pyramidal peaks, and crevasses, moraines, till deposits, water channels and screed flows. The lower ablation zone of Chhota Shigri glacier is covered by surface moraine and debris. The moraine near the snout is spread over 0.5km and thus the glacier is entirely hidden under the ground moraines.

**Lateral moraines**: Two principal lateral moraines are well developed along the sides of the glacier. The eastern moraine is 4.5km long from 4750m and reaches down to 4,100m. The western lateral moraine is about 4.8km and originates from 4800m and extends up to 4200m in a narrow ridge oriented along the north-south direction (Dobhal et al., 1995).
The lateral moraine deposits (Figure 1.4) are present along the margins of the glacier. They are abundant on the eastern margin of the Chhota Shigri glacier and are scarcely present on the western margin. Flow coming from eastern and western side of the glacier merges into main glacier through a medial moraine present in the upper ablation. The western lateral moraine is exposed from 32° 13’ 48” N and 77° 30’ E at an altitude of 4950m, which extend northwards to the snout at 32° 16’ 12” N and 77° 31’ 42” E. This series of moraine further extends up to a distance of approximately 2.65km northward downstream from the snout. The lateral moraines on the eastern margin of the Chhota Shigri glacier extends from 32° 16’ 12” N and 77° 31’ 42” E at an altitude of 4950m from the upper ablation zone and gets buried for a distance of around 60m. The eastern morainic deposition again starts from 32° 15’ 05” N and 77° 31’ 48” E to 32° 16’ 12” N and 77° 31’ 48” E and becomes continuous for the rest of its course which is approximately 3.34km.

**Figure 1.4** Lateral moraine of Chhota Shigri glacier *(GRG, JNU 2008)*

**Figure 1.5** Medial moraine on Chhota Shigri glacier *(GRG, JNU 2006)*

**Medial Moraines:** The medial moraines are represented by prominent uplifted glacier surfaces. It formed when the inside lateral moraines of two glaciers merge together and move down forming a ridge down the center of the combined glaciers. Like lateral moraines, medial moraines also start from the upper part of the glacier (Chaujar, 1987). According to Shruti (2008) the medial moraine in Chhota Shigri glacier extended from 32° 13’ 12” N and 77° 30’ 36” E at an altitude of 4850 m to 32° 15’ N and 77° 31’ 12” E at an altitude of 4575m having a stretch of about 3.5 km (Figure 1.5). A new streak of morainic depositions was found to be exposed between the eastern morainic deposits and the medial moraine at an
altitude between 4800m to 4750m at 32° 13’ 47.64” N and 77° 31’ 36.10” E to 32° 13’ 48.38” N and 77° 30’ 39.26” E.

*Terminal Moraines:* A well developed terminal moraine indicates that the ice remained stationary for a considerable period of time. Two morainic loops of terminal moraines have been observed. The first loop covers a distance of 0.58 km whereas second loop extends for a distance of about 2.08 km (Shruti, 2008). The terminal moraines are also noticed in downstream along both sides of the Chhota Shigri nala fed by the snowmelt of the glacier.
Crevasse patterns

Crevasse patterns are prominent surface features on the glaciers and are developed by the deformation of ice (Figure 1.8). They form open fractures in response to the stress field at the surface. They are classified according to the directions of the stress; such as transverse, longitudinal or radial. In the Chhota Shigri glacier, transverse crevasses are predominant over all the parts of the glacier (Chaujar, 1987), i.e. they run almost at right angles to the length of the glacier in E-W direction where as longitudinal crevasses are mainly found in the lower part and side of the glacier valley, the radial and marginal crevasses are recognized near the snout or lower part of the glacier (Chansarkar and Dobhal, 1988). The old crevasses developed near the equilibrium line are healed up near the middle part of the ablation zone and often it is seen that the surface melt water penetrates the ice body along such crevasses and form subglacial channels. The crevasses in this glacier show that most of them are 20-40m long confined to the upper ablation zone and 40-200m near the equilibrium line (Dobhal et al., 1995). These features are oriented mostly in NW and NE directions with a dip slope of about 45-80°. Kumar (1991) focused on flow dynamics and has inferred that the vertical component of ice flow is downward in and around the equilibrium line while it is upward in the lower part of ablation zone. There is limited geomorphological work carried out till date on Chhota Shigri glacier. Hence there is a need for such detailed studies in near future.

1.2.3 Climate

Climate is the most important factor that influences glacier dynamics. Any change in the carbon dioxide/greenhouse gas concentration in atmosphere affects the glacier health by changing the temperature regime and is reflected in the retreat or advance of glaciers. Hence meteorological studies of glacier basins are highly imperative to understand climate-glacier interactions.

The climate of Chhota Sigiri and its adjoining area is wet and cool. Climatic records from the nearest meteorological station in Keylong are not readily accessible. Hence available older data and other sources of meteorological data have been used by researchers. NCEP/NCAR re-analyses data was used by Wagnon et al., (2007) to understand climate and mass balance relationship. Two distinct precipitation regimes (Bookhagen and Burbank, 2006) are prevalent in this glacier basin. This is typical climate of monsoon-arid transition zone where both the summer Asian monsoon and the winter mid-latitude westerlies influence the climate.
regime. The Chandra River valley, where the glacier is situated, is drier than the southern slopes of the Pir Panjal range. This is the leeward effect of the main ridge mostly oriented W-E, thus preventing part of the monsoon flux from reaching the valley (Bookhagen and Burbank, 2006). The upper accumulation zone had >65% humidity and experiences occasional precipitation in the form of snow and rain drizzle. The annual precipitation of on the glacier is in the range of 150-200cm of snow (Nijampurkar and Rao, 1992). The lower reaches of the glacier are in the dry cold valley zone. The region is characterized by a cold season extending from October to April.

**Meteorological Studies:** The Himalayan glaciers possess most rugged topography coupled with extreme climatic conditions making them one of the most hostile environments in the world. Special efforts, therefore, are needed to carry out meteorological studies in the glacier. In glacier monitoring the important meteorological parameters besides radiation and temperature are wind speed, rainfall and air moisture. To some extent, rainfall on the glacier surface and heat from bedrock also adds to the melt from the glaciated zone (Upadhyay et al., 1989).


Initially three observatories were set up in 1986 by (Rizvi, 1987) but continued with only two observatories in the year 1987, 1988 and 1989; one observatory over the glacier surface known as glacier camp observatory and the other in the snout area designated as base camp observatory. Glacier camp observatory was sited at an elevation between 4500 and 4700m, very near to the accumulation zone of the glacier. Base camp observatory was near the snout between 3800 to 3900m. During 1986 - 1988, the weather parameters recorded at these observatories were (a) dry bulb, wet bulb, maximum and minimum temperatures (b) speed and direction of wind (c) rainfall (d) clouds (e) visibility (f) humidity and (g) past and current weather at synoptic hours. In addition to these, the total hours of sunshine and hourly measurements of global solar radiation and albedo were observed. The global solar radiation and albedo values over rock exposures, fresh snow surface, and dirty ice surface and over old
snow located in the different parts of the glacier valley were observed (Purohit et al., 1989).

In 2003 an Automatic Weather Station (AWS) was installed on the lower ablation zone of the glacier. It was installed on the debris covered part of the Chhota Shigri glacier at 32° 16’ N and 77° 32’ E having an altitude of 4343m amsl. But only seven days’ data could be collected due to malfunctioning of AWS. The AWS observations recorded were of half hourly interval with an integration time of 10 seconds (Sharma, 2007). The meteorological parameters recorded by AWS are presented in Table 1.7 and Figure 1.10.

In 2009, an AWS was installed near to the ELA (Equilibrium Line Altitude) on eastern flank of the glacier at an altitude of 4980m amsl, a first attempt to collect weather data at this altitude on this glacier and one among the very few glaciers of Indian Himalaya which have meteorological station at this altitude. The AWS observations recorded were hourly with an integration time of 15 minutes (JNU-IFCPAR, 2009). The meteorological parameters recorded by AWS are presented in graph (Figure 1.11). Rainfall data were not collected in 2003 and 2009 due to lack of rainfall sensor.

Temperature recorded over the glacier surface shows a mean diurnal variation of 9.1°C. Highest maximum temperature observed is about 10.5°C, 11°C, 8.1°C, 7.5°C, 9.64°C and 11.85°C and lowest minimum temperature of about -4.5°C, -1.3°C, -5.2°C, -1.6°C, -6.22°C and -13.64°C in 1986, 1987, 1988, 1989, 2003 and 2009 respectively on glacier surface (Table 1.4). Relative humidity over glacier surface was found to vary between 12-99%. Highest maximum Relative humidity observed is about 99%, 97%, 91%, 93%, 78.5% and 98.7% and lowest minimum Relative humidity of about 12%, 51%, 60%, 73%, 10.1% and 7.1% in 1986, 1987, 1988, 1989, 2003 and 2009 respectively (Table 1.4). Vapour pressure shows a variation of about 3mb. ranging from 4.3 to 7.7mb. for all the observations of wet bulb taken over the glacier surface (Rizvi,1987; Upadhyay et al, 1989; Purohit et al., 1991). The range of temperature and mean diurnal temperature as well as RH observed both at glacier and base camp are given in Table 1.4 and 1.5 respectively. The variation in observed data might be due to difference in observatories’ altitude and observation time.

The half hourly variations of the temperature, relative humidity, net radiation and total solar flux in the lower ablation zone during 2003 are presented (Figure 1.10). The maximum relative humidity was observed during night while minimum was observed between 12:00
noon to 1:00 pm. In 2009, the maximum temperature was 17.5°C on September 7 while the minimum was -13.6°C on October 11. The relative humidity ranges from 7.1% to 98.7% minimum on September 1 and maximum on October 8, 2009. The fifteen minute variation of the temperature and relative humidity have been presented graphically (Figure. 1.11).

**Table 1.4** Observations at glacier surface (*Rizvi, 1987; IMD, 1987; Apte et al., 1988; Kulandaivelu et al., 1989; Upadhyay et al., 1989; Sharma, 2007; JNU-IFCPAR, 2009)

<table>
<thead>
<tr>
<th></th>
<th>1986 (4700m)</th>
<th>1987 (4500m)</th>
<th>1987 (4500m)</th>
<th>1989 (4600m)</th>
<th>2003 (4343m)</th>
<th>2009 (4920m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest max. Temp. °C</td>
<td>10.5</td>
<td>11</td>
<td>8.1</td>
<td>7.5</td>
<td>9.64</td>
<td>11.85</td>
</tr>
<tr>
<td>Lowest min. Temp. °C</td>
<td>-4.5</td>
<td>-1.3</td>
<td>-5.2</td>
<td>-1.6</td>
<td>-2.2</td>
<td>-13.64</td>
</tr>
<tr>
<td>Mean Temp. °C</td>
<td>3.4</td>
<td>3.2</td>
<td>3.2</td>
<td>0.7</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>Highest max. R.H. (%)</td>
<td>99</td>
<td>97</td>
<td>91</td>
<td>93</td>
<td>78.5</td>
<td>98.7</td>
</tr>
<tr>
<td>Lowest min. R.H. (%)</td>
<td>12</td>
<td>51</td>
<td>60</td>
<td>73</td>
<td>10.1</td>
<td>7.1</td>
</tr>
<tr>
<td>Mean R.H. (%)</td>
<td>71</td>
<td>78</td>
<td>78</td>
<td>82</td>
<td>70</td>
<td>63</td>
</tr>
</tbody>
</table>

**Table 1.5** Observations near the base camp (*Rizvi, 1987; Apte et al., 1988; Kulandaivelu et al., 1989; Upadhyay et al., 1989)

<table>
<thead>
<tr>
<th></th>
<th>1986(3816m)</th>
<th>1987(3816m)</th>
<th>1988(3870m)</th>
<th>1989(3870m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest maximum Temp. °C</td>
<td>18</td>
<td>19.6</td>
<td>19.4</td>
<td>17.0</td>
</tr>
<tr>
<td>Lowest minimum Temp. °C</td>
<td>4.5</td>
<td>3.4</td>
<td>3.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Range</td>
<td>13.5</td>
<td>16.2</td>
<td>16.1</td>
<td>16.9</td>
</tr>
<tr>
<td>Mean Temp</td>
<td>10.4</td>
<td>12.8</td>
<td>11.5</td>
<td>9.2</td>
</tr>
<tr>
<td>Highest maximum R.H. (%)</td>
<td>98</td>
<td>88</td>
<td>91</td>
<td>92</td>
</tr>
<tr>
<td>Lowest minimum R.H. (%)</td>
<td>23</td>
<td>32</td>
<td>40</td>
<td>34</td>
</tr>
<tr>
<td>Range</td>
<td>75</td>
<td>56</td>
<td>51</td>
<td>58</td>
</tr>
<tr>
<td>Mean R.H. (%)</td>
<td>70</td>
<td>47</td>
<td>47</td>
<td>59</td>
</tr>
</tbody>
</table>

Wind, varying in speed between 3-15km\(^{-1}\) flows down the slope in south-westerly to southerly in the valley from Sara Umga Pass in south to the Chandra river valley in north (Purohit et al., 1991; Sharma, 2007). Wind is calm in the morning and by afternoon it gains moment and reached a maximum at evening. There was not a single case of heavy rainfall observed during 1988, although it is for very short period. Highest precipitation of rainfall (9mm) was measured on August 15, 1988 otherwise trace amount of precipitation are recorded (Upadhyay et al., 1989; Purohit et al., 1991).

Generally cumulus and stratocumulus clouds amounting to about 3 octa in the morning to 6
or 7 octa in the evening are observed. Other high altitude cirrus clouds are seen besides altocumulus and altostratus in the middle order. Sunshine values up to 8.5hrs have been recorded over the glacier surface during these expeditions (Upadyay et al., 1989). In general, weather is found to be fair in the early noon hours with development of clouds in the afternoon on most occasions. Visibility is usually good in the morning but deteriorates with the low stratus clouds occupying the valley (Rizvi, 1987; Apte et al., 1988; Kulandaivelu et al., 1989; Purohit et al., 1991; Upadyay et al., 1989).

In 2003, the average of the net radiation of 10 seconds’ integration time reached to a maximum of 69.35Wm\(^{-2}\) and the maximum value was observed at about midday. The total solar flux showed a similar pattern for all days except for secondary peaks on Julian days 276 and 280. The maximum value observed were nearly 7000KJm\(^{-2}\) for all days as that of total solar flux with maximum density ranges from 3.8 to 3.9Wm\(^{-2}\) (Sharma, 2007). To know the snow melt value, both global solar radiation and albedo measurements were carried out on snow, old snow, old dry snow, old wet snow, ice and rock exposures at the glacier surface and surrounding area (Upadhyay et al.,1989), with a view to understand variations in the albedo values. The mean value of global radiation of the order of 200 calories per sq. cm. per day is observed. The albedo measured for various exposures in the glacier valley are given in Table 1.6.

**Table 1.6 Albedo for various objects on glacier surface (Upadhyay et al., 1989)**

<table>
<thead>
<tr>
<th>Particular</th>
<th>Albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh snow</td>
<td>70 - 90%</td>
</tr>
<tr>
<td>Dry snow</td>
<td>56 - 86%</td>
</tr>
<tr>
<td>Snow (1-3 days old)</td>
<td>49%</td>
</tr>
<tr>
<td>Old dry snow</td>
<td>44%</td>
</tr>
<tr>
<td>Old wet snow</td>
<td>35%</td>
</tr>
<tr>
<td>Ice (black)</td>
<td>16%</td>
</tr>
<tr>
<td>Rock (surface)</td>
<td>28%</td>
</tr>
</tbody>
</table>

So overall we can say that annual temperature variation near terminus at (4100m) is 15°C to 20°C and near the snow line is 7°C to - 15°C (Sharma, 2007). Annual thermal amplitude is more than 18°C between January and August, the coldest and hottest months respectively.
Figure 1.9  a) Diurnal variation of temperature  b) Diurnal variation of Relative Humidity  c) Albedo of the glacier surface  d) Average hourly values of solar energy  e) wind rose at glacier camp in 1987 on Chhota Shigri glacier (Upadhyay et al., 1989)
During July–August, the temperature ranges from 4°C to 20°C while the annual 0°C temperature is at an altitude of 4900m that creates very cold condition at the Sara - Umga Pass region (Dobhal et al., 1995). During July to September, temperature ranged from -5.2°C to 10.5°C at equilibrium line (4600m amsl) on the glacier, whereas near the snout a maximum temperature of 16°C and a minimum of 4°C was recorded (Dobhal et al., 1995). In the mornings generally clear sky was observed, while strong surface wind began to blow in the afternoon. Cumulus clouds formed during afternoons and were replaced by thick stratus clouds drifting through the Sara Umga Pass from south and by evening covered the glacier completely reducing visibility. Winds were generally light and south to south-westerly in the morning and gained momentum in the afternoon. Rainfall was generally less in quantity but high in frequency.

Table 1.7: Chhota Shigri daily Meteorological Parameters, 2-8 Oct. 2003 (Sharma, 2007)

<table>
<thead>
<tr>
<th>Julion</th>
<th>T_Max °C</th>
<th>T_Min °C</th>
<th>T_Avg °C</th>
<th>RH_Max %</th>
<th>RH_Min %</th>
<th>Rain mm</th>
<th>NR_Max Wm²</th>
<th>NR_Min Wm²</th>
<th>NR_Av Wm²</th>
<th>Flx_d_Max KWm²</th>
<th>Flx_d_Min KWm²</th>
<th>Flx_d_Av KWm²</th>
<th>S-Flux_Tot KJm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>276</td>
<td>4.14</td>
<td>-6.22</td>
<td>-1.41</td>
<td>68.81</td>
<td>26.78</td>
<td>0.00</td>
<td>615.43</td>
<td>265.46</td>
<td>510.37</td>
<td>0.40</td>
<td>0.14</td>
<td>0.35</td>
<td>97755.91</td>
</tr>
<tr>
<td>277</td>
<td>8.86</td>
<td>-6.09</td>
<td>0.31</td>
<td>63.30</td>
<td>10.17</td>
<td>0.00</td>
<td>529.23</td>
<td>355.54</td>
<td>446.22</td>
<td>0.95</td>
<td>0.76</td>
<td>0.87</td>
<td>72014.85</td>
</tr>
<tr>
<td>278</td>
<td>9.64</td>
<td>-4.42</td>
<td>1.61</td>
<td>60.36</td>
<td>11.23</td>
<td>0.00</td>
<td>511.43</td>
<td>346.31</td>
<td>425.64</td>
<td>0.91</td>
<td>0.73</td>
<td>0.82</td>
<td>71106.88</td>
</tr>
<tr>
<td>279</td>
<td>7.99</td>
<td>-4.36</td>
<td>1.27</td>
<td>75.20</td>
<td>10.87</td>
<td>0.00</td>
<td>553.58</td>
<td>387.03</td>
<td>463.48</td>
<td>0.91</td>
<td>0.74</td>
<td>0.82</td>
<td>71034.88</td>
</tr>
<tr>
<td>280</td>
<td>7.04</td>
<td>-4.52</td>
<td>0.95</td>
<td>78.50</td>
<td>25.13</td>
<td>0.00</td>
<td>670.62</td>
<td>321.74</td>
<td>502.23</td>
<td>0.98</td>
<td>0.63</td>
<td>0.81</td>
<td>69682.74</td>
</tr>
<tr>
<td>281</td>
<td>8.57</td>
<td>-4.30</td>
<td>1.41</td>
<td>73.30</td>
<td>22.40</td>
<td>0.00</td>
<td>590.75</td>
<td>327.90</td>
<td>485.79</td>
<td>0.96</td>
<td>0.58</td>
<td>0.85</td>
<td>65752.45</td>
</tr>
</tbody>
</table>

Note: NR = net radiation; Flx_d = incoming solar flux density; S_flux = solar flux; Max= maximum; Av = average; Tot = total
Figure 1.10  a) Half hourly variation of temperature b) Half hourly variation of humidity c) Half hourly variation of total solar flux observed in the lower ablation zone of the Chhota Shigri glacier in 2003 (Sharma, 2007)
1.2.4 Geology

Chhota Shigri glacier lies in the Central Crystalline of the Pir Panjal range of the Indian Himalaya. Geological map of the area around Chhota Shigri glacier (including Bara Shigri, Chhota Darra, behind Sara Umga Pass etc.) is presented in Figure 1.12.
This crystalline axis is comprised mostly of meso- to ketazonal metamorphites, migmatites and gneisses (Kumar et al., 1987). In few places, granitic rocks of different composition and younger age indicate rejuvenation. At 3 km upstream of Chhota Dara, in the upper Chandra valley, older Palaeozoic granitic rocks are exposed. The Haimanta formation overlies these...
with a tectonic break, where black slates, phyllites and fine-grained biotite-schists are exposed (Rawat and Purohit, 1988, Kumar et al., 1987). The slates and phyllites shows a well developed thrust tectonic contact, which forms the crest of the northern ridge. Box type folds with decollement are quite prominent in the Haimanta formation. The brown biotite, with a fine-grained texture, shows intense heating effect, which indicates periodic re-heating of the granite rocks below (Rawat and Purohit, 1988). The various types of granite and gneiss rocks present in the basement also indicate the same activity. Schistose gneiss and Augen gneiss have developed in the granite without any distinct margins. In Chhota Shigri, Rohtang gneiss is dominant (Figure 1.12) throughout the glacier bed (Kumar et al., 1987) while some Chalcopyrite was found in the lateral moraines (Katoch, 1989). The traces of Chalcopyrite were traceable up to the height of 4700m and in such low quantity that it does not indicate any major deposit but only thin veins of these minerals can be expected.

1.2.5 Chhota Shigri, a representative glacier in Indian Himalaya

In 2002, an International Workshop was organized in Chhota Shigri glacier by International Commission on Snow and Ice (ICSI), UNESCO, HKH-Friend and DST in collaboration with JNU with emphasis on glacier mass balance measurements. Chhota Shigri glacier was proposed to be considered as a bench mark glacier during the deliberations. Characters for bench mark glacier recommended by the ICSI are: glacier area neither too small nor too large, altitudinal range is approximately 1000m (to detect ELA variability), well defined catchment, simple geometry, easily accessible, well defined accumulation area, single tongue, insignificant mechanical processes such as avalanches, relatively debris free and smooth surface, etc. In practice all these requirements are hard to meet but they should be considered as guidelines. Chhota Shigri glacier fulfilled most of the above requirements and so it was chosen for long term monitoring as a benchmark glacier in Indian Himalaya.
**Highlights**

Chhota Shigri glacier in India located between 32°11’ - 32°17’ N and 77°29’ - 77°33’ E 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 15.7km² with catchment area of 34.7km². This glacier is influenced alternatively by Asian Monsoon in summer and mid-latitude westerlies in winter. Thus it has two distinct accumulations i.e. summer and winter. The geology of the catchment is dominated by Rohtang gneiss.

Initial monitoring of this glacier began during 1986 to 1989 through Multi Disciplinary Glacier Expeditions organized by Wadia Institute of Himalayan Geology and sponsored by Department of Science & Technology (DST), Govt. of India. During these expeditions, the morphology, bedrock topography, meteorological parameters, hydrogeochemistry as well as the dynamics of this glacier have been surveyed during ablation seasons of 1986 to 1989 period. The detailed topographic map of the Chhota Shigri glacier was prepared by SOI at a scale of 1:10,000 in 1986.

This glacier has been chosen for integrated long term monitoring because it fulfills most characteristics of “Bench Mark” glacier and already had significant amount of existing glaciological database.

Since 2002, scientific community is continuously monitoring the glacier mass balance and surface velocity with limited work on hydrological balance, hydro-geochemistry of meltwater and snout monitoring. Meteorological data collection has started in 2009.
2. Glacier Dynamics

Dynamics of a glacier requires the understanding of the flow of glacier, mass distribution, energy and temperature distribution, entrainment of debris, character of moraine, crevasse formation, etc. It also requires fundamental information of mass balance, depth and temperature of the ice, meteorological data, surface velocity vectors, strain rates, surface gradients, and changes in the surface elevation.

2.1 Snout Fluctuation

Glacier snout position is the simplest indicator of glacier advance or retreat over a period of time which generally happens due to climatic fluctuations. The record of palaeo-fluctuations of the snout can be recreated by comparison of past maps and photographs of different dates with current and continuous survey of the snout position. The Himalayan glacier fluctuation records extend back to over 150 years. The earliest studies concerned with glacier snout fluctuations were made for Chong Kumdan Glacier in 1812 AD by Izzet Ullah. Mayeswki and Jeschke (1979) studied fluctuation records of 122 glaciers in the Himalaya and concluded that most of the glaciers are retreating. During the International Geophysical Year (1957-58) and ‘International Geophysical Decade’ the monitoring of several glaciers like Gangotri, Satopanth, Milam, Poting, Shankalpa, Pindari, Kaphni, Mrigthuni, Burhagal, Maiktoli, Machoi, Sonapani, Bara Shigri, Chhota Shigri, etc has been carried out by Geological Survey of India.

2.1.1 History of snout measurements of the Chhota Shigri glacier

The oldest snout position of the Chhota Shigri glacier is recorded in the SOI Toposheet of 1962 (No. 52H/11 & 12) at a height of 4050m amsl, about 2.5km south of Chandra River near Chhota Darra, and shifted to 4056m from 1984 to 1989 as assessed regularly by EDM survey (Kumar and Dobhal, 1994). Later the Chhota Shigri glacier snout was demarcated in 1995 on 1:50,000 scale by GSI (Sangewar, 1995).

2.1.2 Geomorphological evidence of palaeo-fluctuations of the snout

Six stages of glacier retreat/advance (Figure 2.1) have been identified by delineating the morainic deposits below the present snout position. The small till mound over the old surface indicates it has undergone substantial phases of advance. The different signatures left by the retreat or advancement of Chhota Shigri glacier from time to time is of great interest in
glacier fluctuation measurements (Dobhal, 1992). The main glacier moraine which crosses over to the other side of the Chandra River indicates the existence of the Chhota Shigri glacier as a tributary of the old Chandra Valley Glacier prior to the river. This is corroborated by the long bend in the lower ablation zone of Chhota Shigri glacier and its palaeo-moraines towards NNE. The extent of the glacier in the past is borne out by the lateral and terminal moraines seen near the confluence of Chhota Shigri Nala with Chandra river at an altitude of 3750m amsl. This morainic deposit indicates Stage I of glaciations. The second morainic deposits at 600m south of the Stage I represent Stage II, during which the width of the valley was reduced to about 100-200m with a reduced energy of transportation. Then Stage III destroyed the western limb of Stage II suggesting either an advance of the glacier or a sudden burst at the snout. Stage IV is characterised by a further reduction in the volume and width of the glacier ice. Stages V and VI indicate glacier advance and retreat in recent times which is indicated by continuous morainic deposits.

Figure 2.1 Chhota Shigri glacier with different series of morainic deposits (Dobhal, 1992)
2.1.3 Snout fluctuations in the recent past

The snout of the Chhota Shigri glacier has been retreating in recent times, except in 1987 (Table 2.1), (Figure 2.2 and Figure 2.3).

![Figure 2.2](image1.png)  
**Figure 2.2** Snout positions in 1984 and 1989 demarcated against the position in 1962 (*Dobhal, 1992)*

![Figure 2.3](image2.png)  
**Figure 2.3** The fluctuation of the Chhota Shigri snout mapped during the continuous observations between 1984 and 1989 (*Dobhal, 1992)*

While the snout retreated 165m from 1963 to 1984 with an average retreat of 7.86myr\(^{-1}\), it retreated 60m in the 9 years between 1986 and 1995 with an average retreat of 6.7myr\(^{-1}\). The
surface area vacated by the Chhota Shigri Glacier during 1962 to 1986 was 3629 m² yr⁻¹, while it was only 2286 m² yr⁻¹ between 1986 and 1995 (GSI, 2001).

**Table 2.1** Relative advance/retreat of snout position of Chhota Shigri glacier (1962-2008)

<table>
<thead>
<tr>
<th>Year</th>
<th>Altitude (m amsl)</th>
<th>Snout fluctuation (m)</th>
<th>Period of observation (years)</th>
<th>Advance/Retreat (myr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1962</td>
<td>4050</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1984</td>
<td>-</td>
<td>-165.0</td>
<td>22</td>
<td>-7.5</td>
</tr>
<tr>
<td>1986</td>
<td>4055.15</td>
<td>-5.19</td>
<td>2</td>
<td>-2.6</td>
</tr>
<tr>
<td>1987</td>
<td>4051.40</td>
<td>+17.5</td>
<td>1</td>
<td>+17.5</td>
</tr>
<tr>
<td>1988</td>
<td>4052.60</td>
<td>-22.1</td>
<td>1</td>
<td>-22.1</td>
</tr>
<tr>
<td>1989</td>
<td>4055.65</td>
<td>-19.01</td>
<td>1</td>
<td>-19.01</td>
</tr>
<tr>
<td>1995</td>
<td>-</td>
<td>-35.5</td>
<td>6</td>
<td>-5.9</td>
</tr>
<tr>
<td>2003</td>
<td>-</td>
<td>-800</td>
<td>15</td>
<td>-53.3</td>
</tr>
<tr>
<td>2006</td>
<td>-</td>
<td>-850</td>
<td>34</td>
<td>-25</td>
</tr>
</tbody>
</table>

* Remarks: Initial position taken from SOI toposheet * Position per SOI Air Survey Map of Chhota Shigri * Co-ordinates fixed by WIHG * Co-ordinates fixed by WIHG * Co-ordinates fixed by WIHG * Co-ordinates fixed by WIHG * Recalculated from WIHG & GSI data * Kulkarni et al. (2007) ** Shruti (2008) **

* field based methodology ** remote sensing

The Chhota Shigri snout retreat was estimated to be 53.3 myr⁻¹ between 1988 and 2003 (Kulkarni et al., 2007) by remote sensing and field verification. However, the retreat was estimated to be 25 myr⁻¹ between 1972 and 2006 (Shruti, 2008), but has its own limitation due to different image resolutions. However these studies give annual retreat four to nine times that of GSI. Thus there is a broad consensus among all the above studies that Chhota Shigri glacier has been in a state of retreat for the last 50 years, though the retreat rates obtained are highly variable. Such a wide variation cannot be explained and calls for common standard methodologies to avoid discrepancies and obtain inter-comparable results.
<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Measurement method</th>
<th>Glacier measured</th>
<th>Details</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Traditional</td>
<td>Entire</td>
<td>Surface stakes, snow probing, snow pit method, snow coring.</td>
<td>Ostrem and Stanley, 1966</td>
</tr>
<tr>
<td>2</td>
<td>Snow cover</td>
<td>Entire</td>
<td>-Do-</td>
<td>Zubok, 1975.</td>
</tr>
<tr>
<td>4</td>
<td>Stratigraphical method</td>
<td>Entire/Portion</td>
<td>Multivariate/statistical method, using data obtained from 1 &amp; 3 based on site and year, Similar as above (4a) but with additional correction based upon model of most important melt parameter.</td>
<td>Luboutry, 1974 &amp; Letreguilly, 1984. Young, 1976.</td>
</tr>
</tbody>
</table>

Contd...
<table>
<thead>
<tr>
<th></th>
<th>Method</th>
<th>Category</th>
<th>Description</th>
<th>Reference/Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Terminus position</td>
<td>Entire</td>
<td>Ground survey, remote sensing, aerial photography, glacier flow response model called “inverse problem”</td>
<td>Paterson, 1981.</td>
</tr>
<tr>
<td>10</td>
<td>Velocity parameter</td>
<td>Entire/Portion</td>
<td>Ice flow in vertical/horizontal direction, topographic change.</td>
<td>Meier &amp; Tangborn 1965.</td>
</tr>
</tbody>
</table>
2.2 Glacier Mass Balance

Mass balance of the glacier is defined as the balance between the accumulation and the ablation of the glacier at a given period of time (Bennett and Glasser, 2000).

2.2.1 Different methodologies

There are several methods (glaciological, hydrological, remote sensing, geodic, flux divergent, AAR and ELA) for carrying out the mass balance studies of a glacier, which has been used worldwide (Table 2.2). Field methods are among the best methods for calculating the mass balance of a glacier.

Table 2.3 Mass-balance studies of Himalayan glaciers

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Name of the Glacier</th>
<th>Location</th>
<th>Period of Study</th>
<th>Sp.Bn. (m w.e. a⁻¹)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gara</td>
<td>Himachal</td>
<td>1974 – 1983</td>
<td>-0.324</td>
<td>Raina et al.,1977</td>
</tr>
<tr>
<td>3</td>
<td>Shaune Garang</td>
<td>Himachal</td>
<td>1984 – 1989</td>
<td>-0.407</td>
<td>Singh and Sangewar, 1989</td>
</tr>
<tr>
<td>5</td>
<td>Changme Khangma</td>
<td>Sikkim</td>
<td>1979 – 1986</td>
<td>-0.298</td>
<td>Sharma et al., 1999</td>
</tr>
<tr>
<td>7</td>
<td>Tipra Barnak</td>
<td>Uttrakhand</td>
<td>1981 – 1988</td>
<td>-0.241</td>
<td>Gautam and Mukherjee, 1989</td>
</tr>
<tr>
<td>8</td>
<td>Dunagiri</td>
<td>Uttrakhand</td>
<td>1984 – 1990</td>
<td>-1.038</td>
<td>Srivastava and Swaroop, 1989</td>
</tr>
<tr>
<td>9</td>
<td>Chhota Shigri</td>
<td>Himachal</td>
<td>1987 – 1988</td>
<td>-0.154</td>
<td>Dobhal, 1993</td>
</tr>
<tr>
<td>10</td>
<td>Dokriani</td>
<td>Uttrakhand</td>
<td>1993 – 2000</td>
<td>-0.320</td>
<td>Dobhal et al., 2008</td>
</tr>
</tbody>
</table>

2.2.2 Status of mass balance studies in the Indian Himalaya

Mass balance studies of Himalayan glaciers were initiated by GSI in 1974 on Gara glacier in Himachal Pradesh (Raina et al., 1977). Department of Science and Technology (Govt. Of India) launched an all India coordinated programme on Himalayan glaciers in 1986, and Chhota Shigri glacier, Himachal Pradesh was selected for multidisciplinary studies. In 1990s, Dokriani
glacier in Garhwal and Nardu glacier in Himachal were taken up for detailed studies with special emphasis on mass balance. From 2002 onwards, mass balance monitoring of Chhota Shigri has been continuously carried out by JNU. The overall results of the mass balance studies are compiled in Table 2.3.

### 2.2.3 Mass Balance studies in Chhota Shigri glacier

Mass balance studies on the Chhota Shigri glacier can be divided into two phases, phase I during 1986 - 1989 and Phase II from 2002.

#### 2.2.3.1 Phase I (1986 – 1989)

Department of Science and Technology, New Delhi organised multidisciplinary glacier expeditions to Chhota Shigri during phase I. Glaciological method was used to calculate the mass balance of the glacier. The stakes were fixed at a ratio of 8 to 10 stakes per square km. The measurement of these stakes were made two or three times during the period from August to early September. Metallic stakes of 2m to 3.5m length were used. These stakes were vertically driven through the surface with the help of pouring hot water around the stake and later the shallow portion was packed with snow and ice so that they freeze in its place. The surface ablation was measured by measuring the exposed length above the ice surface at different time intervals. The difference between the initial length of stake and length measured after a few days gives the measurement of the extent of ablation or accumulation.

### Table 2.4 Accumulation/ablation in water equivalent during 1987 (Dobhal, 1992)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Total Area (m²)</th>
<th>Height (m)</th>
<th>Volume (m³)</th>
<th>Density (g/cm³)</th>
<th>Accumulation/Ablation (m³ weq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000-4300</td>
<td>283200</td>
<td>-0.97</td>
<td>-274704</td>
<td>0.90</td>
<td>-247233.60</td>
</tr>
<tr>
<td>4300-4600</td>
<td>1173500</td>
<td>-0.75</td>
<td>-880125</td>
<td>0.81</td>
<td>-712901.25</td>
</tr>
<tr>
<td>4600-4800</td>
<td>2093200</td>
<td>-0.35</td>
<td>-732620</td>
<td>0.67</td>
<td>-490855.40</td>
</tr>
<tr>
<td>4800-5300</td>
<td>3666200</td>
<td>+0.21</td>
<td>769920</td>
<td>0.57</td>
<td>+438844.14</td>
</tr>
</tbody>
</table>
Table 2.5 Accumulation/ablation in water equivalent during 1988 *(Dobhal, 1992)*

<table>
<thead>
<tr>
<th>Zone</th>
<th>Total Area (m²)</th>
<th>Height (m)</th>
<th>Volume (m³)</th>
<th>Density (g cm⁻²)</th>
<th>Accumulation/Ablation (m³ weq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000-4300</td>
<td>283200</td>
<td>-1.59</td>
<td>-450288</td>
<td>0.90</td>
<td>-405259.20</td>
</tr>
<tr>
<td>4300-4600</td>
<td>1173500</td>
<td>-1.21</td>
<td>-1419935</td>
<td>0.81</td>
<td>-1150147.35</td>
</tr>
<tr>
<td>4600-4800</td>
<td>2093200</td>
<td>-0.73</td>
<td>-1528036</td>
<td>0.67</td>
<td>-1023784.12</td>
</tr>
<tr>
<td>4800-5300</td>
<td>3666200</td>
<td>+0.40</td>
<td>+1466480</td>
<td>0.57</td>
<td>+835893.6</td>
</tr>
</tbody>
</table>

The summer balance in 1987 and 1988 was calculated by stake measurements for a period of 14 days (03.08.87 to 17.08.87) and 24 days (07.08.88 to 01.09.88) respectively. Dobhal et al. (1995) observed negative mass balance during this period. The results obtained are summarised in Table 2.4 and Table 2.5. The summer net balance is more or less same during both years probably due to short duration of observations.

**2.2.3.2 Phase II**

In 2002 mass balance studies were initiated by School of Environmental Sciences, Jawaharlal Nehru University by installing fourteen environment-friendly bamboo stakes for the first time on the Chhota Shigri glacier. The density of stakes was increased in a phased manner to obtain a high resolution mass balance data.

**Methodology used**

Annual surface mass balance measurements were carried out on Chhota Shigri Glacier by direct glaciological method measuring ablation and accumulation on the glacier at the end of the ablation season every year i.e. end of September or beginning of October. The series of bamboo stakes used in this study are more than 8 meters long, drilled into the glacier by using a portable steam drill (Heucke, 1999).

The details of Glaciological method employed on Chhota Shigri Glacier are given below:

**Creating Stake Network**

In order to know the ablation and accumulation of the glacier, a network of well-distributed stakes at different altitudes ranging from 4300m amsl to 5200m amsl were placed throughout the glacier since 2002.
Figure 2.4 Distribution of stakes on the Chhota Shigri Glacier (Linda, 2008)

**Stake Location**

The ablation pattern is much more uniform as compared to the accumulation pattern and thus point measurements can be representative over large areas. Keeping this in mind, the stakes were installed along the centre line of the glacier at suitable intervals. Some of the stakes were placed transversely to the central longitudinal axis in order to monitor the difference in accumulation pattern resulting from wind distribution, shading or avalanching. The stakes were installed more in the ablation zone in order to calculate the rate of ablation precisely. Each stake was installed in such a manner that it represented that part of the glacier where it stands (Figure 2.4). Finally the exact position of the installed stake on the glacier surface was recorded by using Differential Global Positioning System (DGPS).
Installation and Numbering System

A logical system of stake numbering has been followed to easily identify and measure the stake readings. 1.8m – 2.0m stake segments were attached to get stake lengths of 10 to 12m, to cope up with the high ablation rates in mid-latitude glaciers. The stakes of different years were marked differently (apart from the number of the individual set of stakes). A particular stake consisted of several independent pieces and each set of stake was numbered in a logical manner during installation. Each piece was engraved with symbols at its neck using a hacksaw blade like I, II, III, IIII, IIIII, etc; which represented stake piece number 1, 2, 3, 4, 5 respectively. Each set of stakes throughout the glacier were numbered using roman numerals as I, II, III, IV, V……XXIV, etc.

The installation of the bamboo stakes was done by putting the segment I at the bottom and the rest in ascending order from bottom to top i.e. II, III, IIII, IIIII, etc. Adjacent segments of a stake were tied together with the help of a steel wire drawn through holes drilled at the end of each piece. The wire was so tied as to make easy fall-out of the upper stake avoiding any breakage. The numbering of the segments was done with the help of a hacksaw blade as I, II, III, IIII and IIIII at the top end of each piece (Fig. 2.5).
Figure 2.5 Numbering of bamboo segments used on the Chhota Shigri Glacier
Technique for Inserting Stakes

In this study a light portable steam driven ice drill (Heucke, 1999) was used successfully for installing stakes in ablation and accumulation zones in the glacier (Figure 2.6).

Figure 2.6 Diagram of the portable steam driven drill (Heucke, 1999)

Replacement of Stakes

Stakes were replaced annually by inserting the new ones as close as possible to the “original” stake position that existed in the last ablation season using DGPS.

Installing and Relocating Stakes in the Accumulation Zone

In the accumulation zone, single stakes of 4 – 5m were used, keeping the exposed ends long enough to know the accumulation in the consecutive year. In order to locate stakes buried under snow, a microwave reflector system consisting of detector which is a directional radio transmitter/receiver, and a small reflector tag was used (Ostrem and Brugman, 1991). Apart from the “Recco” reflector tag, some blue power or saw dust was also sprayed around the foot of the accumulation stakes; this facilitates easy identification of previous year surface while digging snow pit for accumulation measurement.

Ablation Measurement

For net ablation measurement the length of stakes above the glacier surface is measured at two successive dates (t₁ and t₂). The depth of snow (D) over ice surface is also measured. The
difference between stake lengths buried in ice (L) and snow depths at t₁ and t₂ dates gives the specific ablation (ΔS) at this point. Exposed stake lengths and snow depths were measured at each stake and density factor for ice (Dᵢ) and snow (Dₛ) at each measuring point was also applied.

\[ \Delta S = Dᵢ[L (t₂) - L (t₁)] + Dₛ[D (t₂) - D (t₁)] \]

Where,

- ΔS = Specific ablation
- t₁ = Year of Initial Measurement
- t₂ = Year of subsequent Measurement
- L = Length of stakes buried in ice
- D = Depth of snow
- Dᵢ = Density of ice
- Dₛ = Density of snow

**Accumulation measurement**

Accumulation was calculated in terms of water equivalent by measuring the snow depth and applying a snow density factor at each measuring point.

This is achieved either by snow pit or snow core studies. Snow pits dug in specific points in the accumulation zone to know the yearly accumulation by studying the snow stratigraphy. The previous year surface was identified from the dirty ice layer or a blue line, if blue powder was used. Snow density (ρ) at specific depth intervals was calculated by:

\[ \rho = \frac{M}{V} \]

Where, M is the mass of snow collected in known volume, V.
Plate 2.1 (a) & (b) Density measurements on the Chhota Shigri Glacier
**Mass Balance Calculation**

The ablation and accumulation values are integrated over the glacier to calculate the mass balance. The overall specific mass balance, $b_n$, is calculated according to:

$$b_n = \sum b_i \left( \frac{s_i}{S} \right) \text{ (in m weq)}$$

Where $b_i$ is the mass balance of the altitudinal range, $i$, of area $s_i$, and $S$ is the total glacier area. For each altitudinal range, $b_i$ is obtained from the corresponding stake readings or net accumulation measurements.

The annual mass balance observed on Chhota Shigri glacier between 2002 and 2010 are given in Table 2.6 and Figure 2.7. Eight years of annual mass balance studies indicate that the glacier experienced overall negative balance, with positive balances in 2005, 2009 and 2010. The specific balances vary from -1.4 m weq (2002-2003) to +0.33 m weq (2009-2010). Field observations during the positive years showed heavy accumulation with snow cover even in the ablation season. Ablation pattern of Chhota Shigri glacier is similar to the mid latitude glaciers, with mean vertical gradient of 0.7 m weq (100)\(^1\) similar to those reported in the Alps (Wagnon et al., 2007).

**Table 2.6** Specific mass balance for 2002 – 2010 (*Wagnon et al., 2007; JNU-SAC, 2008; JNU-IFCPAR, 2009,2010; JNU-DST, 2011*)

<table>
<thead>
<tr>
<th>Year</th>
<th>Specific Balance (m weq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002 – 2003</td>
<td>-1.4</td>
</tr>
<tr>
<td>2003 – 2004</td>
<td>-1.2</td>
</tr>
<tr>
<td>2004 – 2005</td>
<td>0.1</td>
</tr>
<tr>
<td>2005 – 2006</td>
<td>-1.4</td>
</tr>
<tr>
<td>2006 – 2007</td>
<td>-1.3</td>
</tr>
<tr>
<td>2007 – 2008</td>
<td>-0.93</td>
</tr>
<tr>
<td>2008-2009</td>
<td>0.13</td>
</tr>
<tr>
<td>2009-2010</td>
<td>0.33</td>
</tr>
</tbody>
</table>
2.3 Equilibrium Line Altitude (ELA) and Accumulation Area Ratio (AAR)

Equilibrium line altitude (ELA) is the altitude where the mass balance is zero i.e. the rate of glacial loss is equal to the rate of glacial gain. Accumulation area ratio (AAR) is the ratio of the accumulation zone to the total area of the glacier.

For calculating the equilibrium line altitude reconnaissance method was used in the first phase of observations. In this method the snow line is used for demarcating the equilibrium line mainly in summer. This is further used for calculating AAR. It was found that if AAR value is more than 70%, it represents positive mass balance and if less than 70%, it is negative mass balance and the value 70% corresponds to net balance as zero. Alternatively, the elevation of the equilibrium line can be determined and its variation from year to year can be used to find out the yearly net balance of a glacier.

The accumulation area ratio (AAR) was calculated by demarcating the equilibrium line altitude by snow line. It was done by mapping the snow line in the field and also by using aerial photographs. AAR thus calculated is shown in Table 2.7.
Table 2.7  Equilibrium line altitude (ELA) and Area accumulation ratio (AAR) of Chhota Shigri glacier during 1987 to 1988 (Dobhal, 1992)

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Years</th>
<th>ELA (m amsl)</th>
<th>Accumulation Area (km²)</th>
<th>Ablation Area (km²)</th>
<th>AAR Value (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1987</td>
<td>4650</td>
<td>6.425</td>
<td>2.325</td>
<td>73</td>
<td>Positive</td>
</tr>
<tr>
<td>2</td>
<td>1988</td>
<td>4700</td>
<td>4.150</td>
<td>4.600</td>
<td>59</td>
<td>Negative</td>
</tr>
<tr>
<td>3</td>
<td>1989</td>
<td>4840</td>
<td>3.025</td>
<td>5.735</td>
<td>65</td>
<td>Negative</td>
</tr>
</tbody>
</table>

During the second phase of observations the ELA is calculated from ablation and accumulation values obtained in the field. The ELA was further used for calculating the AAR of the glacier (Table 2.8). The AAR for the negative mass balance years is found to be less than 40%, while those for positive balance years it was more than 60%. The difference in ELA - AAR relationship between the first and second phases could be due to the difference in glacier area considered in these studies.

Table 2.8  AAR and ELA for the studied period 2002 – 2010 (Wagnon et al., 2007; JNU-SAC, 2008; JNU-IFCPAR, 2009,2010; JNU-DST, 2011)

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Years</th>
<th>ELA (m masl)</th>
<th>Accumulation Area (km²)</th>
<th>Ablation Area (km²)</th>
<th>AAR Value (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2003</td>
<td>5170</td>
<td>4.839</td>
<td>10.880</td>
<td>31</td>
<td>Negative</td>
</tr>
<tr>
<td>2</td>
<td>2004</td>
<td>5165</td>
<td>4.951</td>
<td>10.767</td>
<td>31</td>
<td>Negative</td>
</tr>
<tr>
<td>3</td>
<td>2005</td>
<td>4855</td>
<td>11.575</td>
<td>4.143</td>
<td>74</td>
<td>Positive</td>
</tr>
<tr>
<td>4</td>
<td>2006</td>
<td>5185</td>
<td>4.502</td>
<td>11.216</td>
<td>29</td>
<td>Negative</td>
</tr>
<tr>
<td>5</td>
<td>2007</td>
<td>5130</td>
<td>5.707</td>
<td>10.012</td>
<td>36</td>
<td>Negative</td>
</tr>
<tr>
<td>6</td>
<td>2008</td>
<td>5120</td>
<td>5.916</td>
<td>9.802</td>
<td>37</td>
<td>Negative</td>
</tr>
<tr>
<td>7</td>
<td>2009</td>
<td>4980</td>
<td>9.891</td>
<td>5.809</td>
<td>63</td>
<td>Positive</td>
</tr>
<tr>
<td>8</td>
<td>2010</td>
<td>4930</td>
<td>10.962</td>
<td>4.756</td>
<td>70</td>
<td>Positive</td>
</tr>
</tbody>
</table>
2.4 Surface Velocity

Surface velocity of Chhota Shigri glacier was monitored during 1987–1988 with the help of a stake network (Rawat et al., 1989; Dobhal et al., 1995). Horizontal and vertical flow components and mass flux pattern were evaluated along the longitudinal axis and twenty cross sections taken on the glacier. The horizontal and absolute vertical coordinates of stakes were determined during each expedition using EDM survey. Maximum surface velocity along the centre line was recorded near the ELA and minimum at about 4800m amsl elevation where the glacier is thickest and the valley is wide.

The maximum and minimum horizontal surface velocity, vertical component of velocity and mass flux during August – September 1988, 1987 – 1988 are given in Table 2.9. There was remarkable change in horizontal surface velocity which decreased from 73.16ma⁻¹ to 32.60 ma⁻¹ during 1985-1988 as shown in Table 2.10 (Kumar, 1988).

Table 2.9 Maximum and Minimum surface velocity, vertical component and mass flux during 1987 – 88 and 1988 (Rawat et al, 1989; Kumar, 1988)

<table>
<thead>
<tr>
<th>Description</th>
<th>Velocity (m yr⁻¹)</th>
<th>Height (m amsl)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>August - September 1988</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum surface velocity</td>
<td>60.24</td>
<td>4617</td>
</tr>
<tr>
<td>Minimum surface velocity (ablation)</td>
<td>28.20</td>
<td>4361</td>
</tr>
<tr>
<td>Minimum surface velocity (accumulation)</td>
<td>30.47</td>
<td>4981</td>
</tr>
<tr>
<td>Maximum vertical component of velocity</td>
<td>11.70</td>
<td>4982</td>
</tr>
<tr>
<td>Minimum vertical component of velocity</td>
<td>0.50</td>
<td>4695</td>
</tr>
<tr>
<td>Maximum mass flux</td>
<td>+20.30</td>
<td>4387</td>
</tr>
<tr>
<td>Minimum mass flux</td>
<td>-4.20</td>
<td>4982</td>
</tr>
<tr>
<td><strong>1987 – 1988</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum surface velocity</td>
<td>42.43</td>
<td>4721</td>
</tr>
<tr>
<td>Minimum surface velocity (ablation)</td>
<td>25.70</td>
<td>4387</td>
</tr>
<tr>
<td>Minimum surface velocity (accumulation)</td>
<td>32.84</td>
<td>4746</td>
</tr>
<tr>
<td>Maximum vertical component of velocity</td>
<td>2.26</td>
<td>4781</td>
</tr>
<tr>
<td>Minimum vertical component of velocity</td>
<td>0.10</td>
<td>4468</td>
</tr>
<tr>
<td>Maximum mass flux</td>
<td>+0.16</td>
<td>4543</td>
</tr>
<tr>
<td>Minimum mass flux</td>
<td>-0.32</td>
<td>4360</td>
</tr>
</tbody>
</table>
Table 2.10 Mean horizontal surface velocity from 1985 to 1988 (Kumar, 1988)

<table>
<thead>
<tr>
<th>Year</th>
<th>Mean surface velocity (myr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985-86</td>
<td>73.16</td>
</tr>
<tr>
<td>1986-87</td>
<td>26.44</td>
</tr>
<tr>
<td>1987-88</td>
<td>32.6</td>
</tr>
</tbody>
</table>

After a gap of several years, surface velocity measurements on Chhota Shigri glacier were revived in 2003 using DGPS. The coordinates of the same stake were compared for two consecutive years in order to know the yearly surface velocity at that point (Table 2.11).

Table 2.11 Surface velocity determined by the stakes on the Chhota Shigri glacier (Wagnon et al., 2007)

<table>
<thead>
<tr>
<th>Year</th>
<th>Surface Velocity (myr(^{-1}))</th>
<th>Surface velocity (myr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper ablation Zone</td>
<td>Lower ablation zone</td>
</tr>
<tr>
<td></td>
<td>(5000- 4500m amsl)</td>
<td>(&lt; 4500m amsl)</td>
</tr>
<tr>
<td>2003 – 2004</td>
<td>38.5</td>
<td>29</td>
</tr>
<tr>
<td>2004 – 2005</td>
<td>37</td>
<td>25.5</td>
</tr>
<tr>
<td>2005 – 2006</td>
<td>36</td>
<td>27</td>
</tr>
<tr>
<td>2006 – 2007</td>
<td>37.5</td>
<td>28</td>
</tr>
</tbody>
</table>

The velocity in the upper ablation zone (4600 – 5000m) was about 36myr \(^{-1}\) where as it was 26myr \(^{-1}\) in the lower ablation zone (below 4600m). Two peaks of surface velocity were observed at 3km and 6km from the snout (at 4600m amsl and 4850m amsl respectively). Summer velocities were found to be little higher than the annual velocities.

2.5 Energy Balance

To study the energy balance over the Chhota Shigri glacier, observations were made at different altitudes (Bhutiyani, 1989). The energy fluxes over the glacier were calculated using the modified energy balance equation since conductive heat flux is negligible:

\[ Q_m = Q_i - Q_g + Q_s + Q_l \]
Various components of the energy balance equation were calculated using following expressions:

\[ Qi = Qa (1 - \alpha) \]
\[ Qg = 60 \times 24 \times 0.826 \times 10^{-10} (0.757 Ta^4 - Ts^4) [1 - (1 - 0.024 Z) N] \]
\[ Qs = 6.811 \times V_1 \times 0.239 (Ta - Ts) \]
\[ Qi = 6.811 \times V_1 \times 680/p \times 0.622 (Qi.RH - Q_o) \]

Where

- \( Qa = \) Insolation per day
- \( \alpha = \) Albedo expressed as decimal fraction
- \( Ta = \) Mean air temperature in °K
- \( Ts = \) Glacier surface temperature in °K
- \( X = \) Height of cloud base in thousands of feet
- \( N = \) Amount of cloud cover expressed as a decimal fraction
- \( V_1 = \) Wind speed in kmh\(^{-1}\)
- \( P = \) Pressure in mb
- \( RH = \) Relative humidity expressed as a decimal fraction
- \( Qi \) and \( Q_o = \) Saturation vapour pressure in mb over water & ice respectively

The energy fluxes, net energy available, mean air temperature, wind speed along with the amount of the glacier melt per day in centimetres were calculated for various altitudinal zones.

In the ablation zone, the albedo values being small (10 – 20% for glacier ice and 42% for firm), insolation is the major contributor to the energy budget. The contribution due to sensible heat is also significant in these zones. In the accumulation area, due to high albedo values (because of fresh snow), the contribution due to insolation is fairly low and is almost negated by net longwave radiation and latent heat flux resulting in no effective melting on the surface except for few days during the observation period (Bhutiyani, 1989).

Hasnain & Sen, (1989) computed short-term energy fluxes by measuring the mean daily radiation flux, which ranges from 136 to 262 Wm\(^{-2}\) and the sensible heat flux, which varies from 18 to 91Wm\(^{-2}\). The solar radiation (84%), sensible heat flux (21%) and latent heat flux (-5%) were the main contributors to the energy fluxes.
**Highlights**

Snout fluctuations in Chhota Shigri glacier vary from $5.9 \text{myr}^{-1}$ to $53.3 \text{myr}^{-1}$. Though most of the studies show retreat less than $20 \text{m yr}^{-1}$. The unusually large retreat shown in a couple of studies could be due to different methodologies adopted.

Eight years of annual mass balance studies indicate that the glacier experienced overall negative balance, with positive balances in 2005, 2009 and 2010. The earlier mass balance study carried out during 1986-88 also shows negative balance, though the observations were only for very short periods, and the area considered was small due to exclusion of the tributaries. The cumulative specific mass balance during 2002 – 2010 was $-5.37 \text{m weq}$.

ELA was calculated from ablation and accumulation values and was used to estimate the AAR of the glacier. During 1987 – 1989 the ELA varied between 4650m amsl to 4700m amsl with AAR varying between 65% to 73%. Whereas studies done between 2002 – 2010 show a variation of ELA between 4855m amsl to 5185m amsl and AAR between 29% to 74% respectively. The difference in ELA - AAR relationship between various authors could be due to the different methodologies adopted.

No significant difference was observed in glacier mean surface velocities observed during 1985 – 1988 and 2003 – 2007.

Preliminary energy budget studies could not quantify the specific factors driving the energy balance in Chhota Shigri glacier.

The above facts highlight the need for evolving uniform methodologies to understand the factors controlling glacier dynamics for inter-comparison and precision of data sets. Further, to overcome the discontinuity of mass balance data over a few decades, a mass balance model needs to be developed so that long-term glacier response to climate change can be understood.

An integrated long-term monitoring program to quantify the hydrological, mass and energy balances of the glacier and the role of debris cover on glacier health is imperative to understand the complex processes that affect the future water resource availability in the Indian Himalaya.
3. Chemical Investigations

Glaciers potentially contain a wealth of information on the history of air temperatures, pollution, etc. leading to the study of chemical constituents of glacial snow and ice (Herron, 1982; Wolff and Peel, 1985). In a glaciated catchment, solutes derived from atmospheric deposition are incorporated as solid or liquid precipitation, which allows understanding the impact of air quality on the chemical characteristics of melt water.

Hydrochemical investigations of glacial melt-water helps in identifying the nature and concentration of solute embedded in the underlying lithology as well as contribution from atmospheric deposition. The melt water is further enriched in solute derived by hydrological pathways within the glacier. Thus, in glaciated catchments, solute acquisition processes vary in time and space. Hence, long-term monitoring of chemical signatures helps to quantify the relative contributions of natural and anthropogenic constituents in snow pack and glacial ice melt runoff. Inter-basin variation in the melt water chemistry will help in deciphering the effects of climate on the solute acquisition processes and chemical weathering.

The recent interest in water quality of glacierised areas was largely initiated to elucidate hydrological processes in the inaccessible subglacial environment. As the gaps in our glacio-chemical knowledge are addressed, studies on the quality characteristics of melt waters draining from glaciers and ice sheets have the potential to provide important information about the character of subglacial drainage systems, their evolution over time, the role of terrestrial ice masses in chemical denudation and climate change. An overview of the various chemical investigations undertaken on Chhota Shigri glacier in the last three decades is discussed below.

3.1 Snow and Ice Chemistry

Precipitation (rain/snow) plays a major role in the transfer of chemical constituents from the atmosphere to the glacier. The chemical composition of snow and ice in Chhota Shigri glacier (surface and core) in Chhota Shigri glacier is given in Table 3.1.
<table>
<thead>
<tr>
<th>Sample code</th>
<th>Sample nature</th>
<th>Altitude (m)</th>
<th>Na (µg l⁻¹)</th>
<th>K (µg l⁻¹)</th>
<th>Mg (µg l⁻¹)</th>
<th>Ca (µg l⁻¹)</th>
<th>Cl (µg l⁻¹)</th>
<th>NO₃ (µg l⁻¹)</th>
<th>SO₄ (µg l⁻¹)</th>
<th>Si (µg l⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Snow</td>
<td>4050</td>
<td>678</td>
<td>394</td>
<td>51</td>
<td>204</td>
<td>1229</td>
<td>327</td>
<td>141</td>
<td>270</td>
</tr>
<tr>
<td>2.</td>
<td>Snow</td>
<td>4150</td>
<td>240</td>
<td>216</td>
<td>57</td>
<td>106</td>
<td>521</td>
<td>337</td>
<td>164</td>
<td>690</td>
</tr>
<tr>
<td>3.</td>
<td>Snow</td>
<td>4250</td>
<td>369</td>
<td>316</td>
<td>148</td>
<td>277</td>
<td>524</td>
<td>584</td>
<td>239</td>
<td>600</td>
</tr>
<tr>
<td>4.</td>
<td>Snow</td>
<td>4350</td>
<td>288</td>
<td>267</td>
<td>142</td>
<td>228</td>
<td>443</td>
<td>855</td>
<td>209</td>
<td>570</td>
</tr>
<tr>
<td>5.</td>
<td>Snow</td>
<td>4450</td>
<td>189</td>
<td>166</td>
<td>74</td>
<td>131</td>
<td>438</td>
<td>351</td>
<td>189</td>
<td>345</td>
</tr>
<tr>
<td>6.</td>
<td>Snow</td>
<td>4550</td>
<td>202</td>
<td>190</td>
<td>103</td>
<td>179</td>
<td>422</td>
<td>343</td>
<td>347</td>
<td>480</td>
</tr>
<tr>
<td>7.</td>
<td>Snow</td>
<td>4650</td>
<td>329</td>
<td>190</td>
<td>193</td>
<td>543</td>
<td>667</td>
<td>2994</td>
<td>-</td>
<td>540</td>
</tr>
<tr>
<td>8.</td>
<td>Snow</td>
<td>4750</td>
<td>983</td>
<td>495</td>
<td>46</td>
<td>155</td>
<td>1780</td>
<td>-</td>
<td>183</td>
<td>30</td>
</tr>
<tr>
<td>20.</td>
<td>Surface ice</td>
<td>4650</td>
<td>537</td>
<td>318</td>
<td>74</td>
<td>228</td>
<td>781</td>
<td>356</td>
<td>-</td>
<td>75</td>
</tr>
<tr>
<td>21.</td>
<td>Surface ice</td>
<td>4550</td>
<td>118</td>
<td>115</td>
<td>28</td>
<td>57</td>
<td>278</td>
<td>270</td>
<td>114</td>
<td>60</td>
</tr>
<tr>
<td>22.</td>
<td>Surface ice</td>
<td>4450</td>
<td>118</td>
<td>64</td>
<td>28</td>
<td>82</td>
<td>245</td>
<td>869</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>23.</td>
<td>Surface ice</td>
<td>4350</td>
<td>125</td>
<td>64</td>
<td>17</td>
<td>30</td>
<td>331</td>
<td>-</td>
<td>-</td>
<td>15</td>
</tr>
<tr>
<td>24.</td>
<td>Surface ice</td>
<td>4150</td>
<td>189</td>
<td>115</td>
<td>34</td>
<td>106</td>
<td>457</td>
<td>220</td>
<td>241</td>
<td>-</td>
</tr>
<tr>
<td>25.</td>
<td>Surface ice</td>
<td>4100</td>
<td>22</td>
<td>90</td>
<td>28</td>
<td>155</td>
<td>149</td>
<td>-</td>
<td>-</td>
<td>90</td>
</tr>
<tr>
<td>80.</td>
<td>Ice/snow core at (4900m)</td>
<td>0-12</td>
<td>288</td>
<td>216</td>
<td>85</td>
<td>252</td>
<td>661</td>
<td>1105</td>
<td>13</td>
<td>180</td>
</tr>
<tr>
<td>81.</td>
<td>Depth (cm)</td>
<td>12-24</td>
<td>1433</td>
<td>495</td>
<td>176</td>
<td>228</td>
<td>3343</td>
<td>943</td>
<td>135</td>
<td>105</td>
</tr>
<tr>
<td>82.</td>
<td>Depth (cm)</td>
<td>24-36</td>
<td>349</td>
<td>267</td>
<td>68</td>
<td>155</td>
<td>624</td>
<td>-</td>
<td>480</td>
<td>15</td>
</tr>
<tr>
<td>83.</td>
<td>Depth (cm)</td>
<td>36-48</td>
<td>150</td>
<td>115</td>
<td>74</td>
<td>106</td>
<td>362</td>
<td>-</td>
<td>364</td>
<td>45</td>
</tr>
<tr>
<td>84.</td>
<td>Depth (cm)</td>
<td>48-60</td>
<td>202</td>
<td>140</td>
<td>23</td>
<td>87</td>
<td>298</td>
<td>498</td>
<td>10</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>85.</td>
<td>Depth (cm)</td>
<td>60-72</td>
<td>99</td>
<td>115</td>
<td>40</td>
<td>82</td>
<td>216</td>
<td>-</td>
<td>359</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>86.</td>
<td>Depth (cm)</td>
<td>72-84</td>
<td>150</td>
<td>115</td>
<td>23</td>
<td>57</td>
<td>287</td>
<td>522</td>
<td>4</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>87.</td>
<td>Depth (cm)</td>
<td>84-96</td>
<td>279</td>
<td>216</td>
<td>28</td>
<td>57</td>
<td>542</td>
<td>453</td>
<td>23</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>88.</td>
<td>Depth (cm)</td>
<td>96-108</td>
<td>202</td>
<td>166</td>
<td>17</td>
<td>57</td>
<td>413</td>
<td>492</td>
<td>35</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>89.</td>
<td>Depth (cm)</td>
<td>108-120</td>
<td>588</td>
<td>419</td>
<td>57</td>
<td>179</td>
<td>1002</td>
<td>722</td>
<td>98</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>90.</td>
<td>Depth (cm)</td>
<td>150-225</td>
<td>1433</td>
<td>571</td>
<td>170</td>
<td>1130</td>
<td>2404</td>
<td>841</td>
<td>627</td>
<td>30</td>
</tr>
<tr>
<td>91.</td>
<td>Depth (cm)</td>
<td>225-300</td>
<td>758</td>
<td>292</td>
<td>74</td>
<td>447</td>
<td>1292</td>
<td>820</td>
<td>284</td>
<td>30</td>
</tr>
<tr>
<td>92.</td>
<td>Depth (cm)</td>
<td>300-360</td>
<td>1372</td>
<td>671</td>
<td>108</td>
<td>691</td>
<td>2100</td>
<td>715</td>
<td>542</td>
<td>60</td>
</tr>
<tr>
<td>93.</td>
<td>Depth (cm)</td>
<td>360-420</td>
<td>1331</td>
<td>546</td>
<td>108</td>
<td>740</td>
<td>2038</td>
<td>752</td>
<td>452</td>
<td>15</td>
</tr>
</tbody>
</table>
The samples of snow and surface ice from shallow pit/core (0–4m) collected in 1987 at an altitude of 4900m amsl in the accumulation zone of the glacier were analyzed for chemical constituents (Nizampurkar et al., 1993). The concentrations of analyzed major ions (Na\(^+\), K\(^+\), Mg\(^{++}\), Ca\(^{++}\), Cl\(^-\), NO\(_3\)\(^-\) and SO\(_4\)\(^{--}\)) and dissolved silica in snow, surface ice, shallow ice core and melt-waters are mainly derived from cyclic salts and local anthropogenic sources. The ionic composition indicates that sea salts evaporated during the summer months from the Arabian Sea that are transported inland and scavenged by the wet precipitation during the winter months over the glaciers of high altitude Himalaya. The sea salt contributions and the concentration peaks are directly related to weather conditions revealed in the snow profile. The contribution of some major ions from anthropogenic and terrestrial sources also controls their chemical compositions.

The average concentrations of major ions are higher in snow as compared to surface ice due to elution in the snowmelt. Most of the salts are concentrated on the snow surface and are easily removed by water percolation. Further, the snowfall during the year 1987 was much higher (~2m) with strong winds and stormy conditions compared to the preceding years, which might have transported the higher flux of elements from their respective sources (Nizampurkar et al., 1993).

The chloride concentration observed in Chhota Shigri is higher by a factor of five than in Tibetan glaciers, and nitrate in snow samples is higher by a factor of seven than those in Ladakh Himalaya, while sulphate is comparable with those from the Kangri glacier (Mayewski et al., 1983; Lyons et al., 1981). Unlike NO\(_3\)\(^-\), the average SO\(_4\)\(^{--}\) concentration in snow samples is much lower than in the ice core samples indicating low level of SO\(_4\)\(^{--}\) in the ambient atmosphere during deposition.

### 3.2 Meltwater Chemistry

Hydrochemical data on meltwaters draining the glaciated basins in the Himalayas are scant. To understand hydro-chemical processes influencing Chhota Shigri glacier, meltwaters draining from the snout were analyzed for major cations and anions as shown in Table 3.2 (Hasnain et al., 1989, Sharma, 2007, Ramanathan et al., 2009). Meltwaters from the glacier surface have low solute content (electrical conductivity 5.0-5.92\(\mu\)S\(\text{cm}^{-1}\); Ca\(^{2+}\) 36.5 \(\mu\text{eq}^{-1}\); Mg\(^{2+}\) 6.7 \(\mu\text{eq}^{-1}\); Na\(^+\) 15.6 \(\mu\text{eq}^{-1}\); K\(^+\) 8.7 \(\mu\text{eq}^{-1}\)) whereas base flow waters are chemically enriched (electrical conductivity 23.2-29.0\(\mu\text{scm}^{-1}\), Ca\(^{2+}\) 45.0-495 \(\mu\text{eq}^{-1}\); Mg\(^{2+}\) 29.1-41.7 \(\mu\text{eq}^{-1}\); Na\(^+\) 30.4-34.8 \(\mu\text{eq}^{-1}\); K\(^+\) 10.3-35.9 \(\mu\text{eq}^{-1}\)).
The water movement within the Chhota Shigri glacier appears to be through the subglacial and englacial channels (Hasnain et al., 1989). The total dissolved solids (TDS) content is generally low as compared to Indian river water quality that are more alkaline and carry more concentrated salts (Subramanian, 1979, Ramanathan et al, 1993). The low solute content in Chhota Shigri meltwaters was attributed to the granitic bedrock of the glacier, which are less prone to weathering.

The meltwaters emerging from the snout appears to contain a higher proportion of subglacial waters than the supraglacial melt. This indicates that the entire solute concentration in meltwater is derived from subsurface environment. Meltwaters flowing through subglacial channels becomes chemically enriched by interacting with basal morainic material (Benzinge et al., 1973).

Since 2003, the School of Environmental Sciences, JNU has been monitoring Chhota Shigri glacier meltwater quality to understand the hydrogeochemical processes and the solute sources of the melt waters. Initially about forty samples were collected for two weeks coinciding with annual mass balance measurements during September-October and analyzed for major dissolved constituents. The melt waters were found to be neutral to slightly alkaline in nature. EC ranged from 66-96μScm⁻¹ in 2003, 73-95μScm⁻¹ in 2004 and 93-133μScm⁻¹ in 2005 with average value of 81μScm⁻¹, 84μScm⁻¹ and 109μScm⁻¹ respectively. In 2005, the high EC probably followed the excess snowfall and resulting high albedo, synchronous with low water discharge. Bicarbonate, sulfate and calcium are the dominant ions in the melt water. These ions are enriched in 2005 probably due to the contribution from multiple sources such as dust/aerosols deposition, etc. Bicarbonate is probably derived from carbonate weathering and partly from silicate weathering. Both cation and anion concentration show an increasing trend from snout to downstream region (discharge site) as observed in other Himalayan glaciers melt water. The maximum concentrations of the ions were observed in the morning due to low discharge and further reduced in afternoon during high discharge period. The dissolved silica concentration is higher due to the physical weathering process along with existing alkaline environment. Gibbs diagram shows that rock weathering induced by precipitation is the most dominant process controlling their water quality. Most of the carbonate is derived from carbonate weathering and silicate weathering as observed from the high ratio of (Ca+Mg) to (Na+K) and (HCO₃⁻)C to (HCO₃⁻)Si. The other ratios c(Ca²⁺+Mg²+)/TZ⁺, c(Ca²⁺+Mg²⁺)/c(Na⁺+K⁺) and c(Na⁺+K⁺)/TZ⁺ also show the dominance
of carbonate weathering followed by silicate weathering. The estimated bicarbonate contribution i.e. 69% comes from carbonate weathering followed by 31% from silicate weathering (Raymahasay, 1986, Ramanathan et al., 2009). Rock weathering followed by precipitation controls the melt water chemistry. These factors result in excess solute transport in Chhota Shigri melt waters and to the Chandra River, which in turn transfer the chemical load to the great Himalayan river systems and to the open ocean. Both cation and anion concentrations show increasing trend from snout to discharge site as observed in other Himalayan glacier melt waters. In general all cation and anion concentrations are maximum in morning and become minimum in afternoon due to dilution effect (Sharma, 2007).

A summary of the meltwater chemistry from Chhota Shigri glacier is given in Table 3.2. In 1987, the study was focused on surface water chemistry including a few glacial run-off samples (Hasnain et al., 1989; Dhanpal, 1990). Supraglacial waters were found to have lower concentration of solutes compared to glacier runoff water, as these get enriched with solutes after interacting with subglacial environment. The concentration of cations and anions are higher during September/October followed by August/September and July/August due to the dilution effect in the high discharge periods coupled with the low residence time in subglacial channels.
Table 3.2 Comparison of meltwater chemistry parameters (values in µeq l⁻¹ except EC and pH)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Supraglacier surface water</td>
<td>6.2-7.2</td>
<td>7.2</td>
<td>7.4</td>
<td>7.5</td>
<td>7.3</td>
<td>6.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glacier runoff water</td>
<td>5.0-5.9</td>
<td>23.2-29.0</td>
<td>19.9-47.3</td>
<td>81.2</td>
<td>84.7</td>
<td>108.9</td>
<td>20.6</td>
<td>42.5</td>
</tr>
<tr>
<td>pH</td>
<td>-</td>
<td>-</td>
<td>144.2-281.9</td>
<td>391</td>
<td>341</td>
<td>522</td>
<td>125.9</td>
<td>218.5</td>
</tr>
<tr>
<td>EC (µs/cm)</td>
<td>-</td>
<td>-</td>
<td>28.1-67.6</td>
<td>15</td>
<td>23</td>
<td>37</td>
<td>14.1</td>
<td>2.8</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>-</td>
<td>-</td>
<td>62.5-145.8</td>
<td>228</td>
<td>328</td>
<td>280</td>
<td>54.7</td>
<td>103.7</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>-</td>
<td>-</td>
<td>73</td>
<td>60</td>
<td>106</td>
<td>-</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>-</td>
<td>-</td>
<td>39</td>
<td>37</td>
<td>56</td>
<td>1.5</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>PO₄³⁻</td>
<td>-</td>
<td>-</td>
<td>48</td>
<td>67</td>
<td>62</td>
<td>26.1</td>
<td>33.4</td>
<td></td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>36.5</td>
<td>45.0-495</td>
<td>105-185</td>
<td>335</td>
<td>325</td>
<td>527</td>
<td>80.5</td>
<td>103.5</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>6.7</td>
<td>29.1-41.7</td>
<td>8.3-16.66</td>
<td>201</td>
<td>224</td>
<td>281</td>
<td>67.1</td>
<td>98.8</td>
</tr>
<tr>
<td>K⁺</td>
<td>8.7</td>
<td>10.3-35.9</td>
<td>25.64-38.46</td>
<td>60</td>
<td>85</td>
<td>88</td>
<td>15.8</td>
<td>28.9</td>
</tr>
<tr>
<td>Na⁺</td>
<td>15.6</td>
<td>30.4-34.8</td>
<td>34.8-69.6</td>
<td>94</td>
<td>105</td>
<td>116</td>
<td>20.1</td>
<td>38.8</td>
</tr>
</tbody>
</table>

3.3 Radio and Stable Isotopic Investigations

Radioactive and stable isotopes and chemical tracers are excellent time markers and climatic indicators which play an important role in the understanding of past climatic, atmospheric, nuclear and chemical records from both polar and non-polar regions (Delmas et al., 1982; Nijampurkar et al., 1982; Von Gunten et al., 1983; Jouzal et al., 1987). Glaciers and ice caps located at high altitude of remote areas in tropical latitudes may contain records extending back for periods of a few hundred to thousand years (Thompson et al., 1990).
Earlier long-lived isotopes such as $^{32}$Si with a half-life of $\sim$140 years (Somayajulu et al., 1987) and $^{210}$Pb (half-life of 22.3 years) have been used to estimate the ages of Himalayan glaciers, using the standard radioactivity decay equation and a simple two component model (Nijampurkar and Rao, 1992).

Systematic isotopic studies based on natural and artificial radioisotopes, stable isotopes and total $\beta$ activity measurements were carried out on Chhota Shigri glacier, Himachal Pradesh. During August 1987, about 70 samples of snow, ice and shallow ice cores were collected from both the accumulation zone and ablation zone of Chhota Shigri glacier for isotopic studies (Table 3.3). Based on $\delta^{18}$O variations in a shallow ice core, the snow accumulation on Chhota Shigri glacier averaged for the 2 years prior to August 1987 was calculated to be 520kgm$^{-2}$a$^{-1}$ (Nijampurkar and Rao, 1992). Using a half-life value of 140 years for $^{32}$Si and assuming the average value of $^{32}$Si concentration in the snow precipitation in the Himalayan region to be 0.7 dpm10$^3$L$^{-1}$ (Nijampurka et al., 1982), a radiometric age of 250 years of snout ice was obtained and the average surface ice flow rate over the past few centuries was calculated to be 28ma$^{-1}$. They observed a mix of at least 55% snow melt and 45% of old ice melt that emerges from the supraglacial lake of Chhota Shigri glacier (Nijampurkar and Rao, 1992).

**Table 3.3** $^{32}$Si concentrations in snout and meltwaters samples from Chhota Shigri glacier (Nijampurkar and Rao, 1992)

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Nature</th>
<th>Volume processed (litre)</th>
<th>$^{32}$P activity (cph)</th>
<th>$^{32}$Si concentration dpm10$^3$L</th>
<th>Radimetric age (yr)</th>
<th>Surface ice flow rate (ma$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS-1</td>
<td>Snout Ice</td>
<td>900</td>
<td>1.50±0.25</td>
<td>0.21±0.04</td>
<td>250</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>(4100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CS-2</td>
<td>Meltwater</td>
<td>950</td>
<td>4.44±0.26</td>
<td>0.47±0.03</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(4000)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^{137}$Cs with a longer half-life (30 year) could be identified in the $\gamma$-ray spectrum of snow samples among the $^{144}$Ce, $^{134}$Cs, $^{125}$Sb, $^{103}$Ru, $^{95}$Zr etc. that were produced during the Chernobyl accident (Sadasivan and Mishra, 1986) collected at different altitudes. They did not observe high total $\beta$ and $^{137}$Cs activities in samples collected at different depths showing that the radioactive clouds bearing Chernobyl fall-out did not penetrate or diffuse beyond 4700m altitude over the glacier and their deposition in the Himalaya (Nijampurkar and Rao, 1992) is much lower, by a factor of at least 15, than that deposited in the Swiss Alps (Haeberli et al., 1988).
Table 3.4 Deposition of total and $^{137}$Cs activities at different altitudes on Chhota Shigri glacier (Nijampurkar and Rao, 1992)

<table>
<thead>
<tr>
<th>Sample Altitude (m)</th>
<th>Total $\beta$ activity ($dphl^{-1}$)</th>
<th>$^{137}$Cs activity ($dphl^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Snow</td>
<td>Ice</td>
</tr>
<tr>
<td>4100</td>
<td>766 ± 12</td>
<td>390 ± 8</td>
</tr>
<tr>
<td>4150</td>
<td>2305 ± 70</td>
<td>-</td>
</tr>
<tr>
<td>4250</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4350</td>
<td>4305 ± 82</td>
<td>248 ± 8</td>
</tr>
<tr>
<td>4450</td>
<td>3911 ± 85</td>
<td>878 ± 19</td>
</tr>
<tr>
<td>4550</td>
<td>8413 ± 235</td>
<td>-</td>
</tr>
<tr>
<td>4650</td>
<td>1613 ± 25</td>
<td>616 ± 8</td>
</tr>
<tr>
<td>4900</td>
<td>656 ± 15</td>
<td>-</td>
</tr>
</tbody>
</table>
Highlights

The sporadic studies of major ions in meltwater throws some light on the character of rock-water interaction in Chhota Shigri glacier catchment. Ionic concentrations show increasing trend from snout to discharge site and are maximum in morning and minimum in afternoon due to dilution effect. However these studies were conducted for a short duration and could not conclusively describe the inter-annual and even inter-seasonal variability in meltwater chemistry.

Radiometric ages of snout ice as well as the melt water emerging from the snout were estimated through radioisotope analyses. Snow accumulation rate of 520kg/a\(^1\) was arrived at through \(^{18}\)O isotope investigations.

The detailed hydrogeochemical processes that characterize this glacier will throw light on various factors controlling the water chemistry including the role of anthropogenic activities on glacier health.
4. Hydrological Investigation

The changes in the hydrological response of a basin will depend on the sources of runoff, climatic conditions, physical characteristics of the basin and the magnitude of projected climatic scenarios (Singh and Bengtsson, 2005). Proglacial discharge is controlled by the geometry of the glacial drainage network and meltwater processes. 1.8gtyr\(^{-1}\) suspended-sediment (about 9% of the total annual load carried from the continents to the oceans worldwide) is transported by three major Himalayan river systems: the Brahmaputra, Ganga and Indus in a combined runoff of 1.19 x 10\(^3\)km\(^3\) (Meybeck, 1976). Melting glaciers provide a key source of water for the Himalayan region in the summer months though the regional hydrological cycle is complicated by Asian monsoon (Barnett et al., 2005). Hence understanding glacier hydrology is crucial for water resource management in this region.

4.1 Discharge Monitoring

In order to decipher the quantum of discharge including sediment load from Chhota Shigri glacier, initial attempts were made by various institutions during the interdisciplinary Expeditions of 1986-1989. Since 2003, discharge and sediment load measurements were carried out coinciding with the mass balance studies.

Discharges were measured by velocity-area method (Figure 4.1) and salt dilution technique. A coefficient of 0.910 was used to compute the average velocity from surface velocity.

\[
\text{Average velocity} = 0.910 \times \text{surface velocity}
\]

Diurnal variation in the discharge was determined by hourly observation of discharge for 48 hr periods. The daily mean discharge was observed between 6m\(^3\)s\(^{-1}\) to 13m\(^3\)s\(^{-1}\). Diurnal discharge observations revealed that high discharge (Q\(_h\)) and low discharge (Q\(_l\)) occurred between 3:30-7:00pm and 3:00-7:00am respectively. The ratio of Q\(_h\) and Q\(_l\) was found to be approximately 1.50 (NIH, 1991).

A lag time of 1 - 2 hours was reported for discharges in the melt water stream in 1988 (Singh & Verdhen, 1989) whereas it was between 2 - 3 hours in 1989 (NIH, 1991). This variation in lag time may be due to changes in Accumulation Area Ratio (AAR) and/or the debris cover in the lower ablation zone, which can be confirmed through modelling approach.
Discharge measurements were also carried out thrice a day at 7:30am, 11:00am and 6:00pm during the same period (Dillon & Sharma, 1988; Vohra, 1989, 1991a). Float method was used for velocity measurements, and the cross section was made using depth measurements at one meter intervals across the gauging site. The average discharge in 1987 was about 10.80 m$^3$s$^{-1}$, whereas it was about 9.9 m$^3$s$^{-1}$ in 1988. Generally the maximum and minimum discharges were observed between 4:00 to 7:00pm and 3:00 to 7:00am respectively. Lack of meteorological data for the Chhota Shigri glacier basin was a limitation in establishing definite climate-discharge relationships.

Related studies conducted during the same period computed the density of snow/firn upto 1m depth on the glacier to be about 0.55 g cm$^{-3}$, with temperatures ranging from -0.5°C to -5.5°C (NIH, 1988). The annual and interannual variations in discharge are mainly controlled by melting rates. The discharge was found to depend mainly on air temperature and it alone explained about 60% of discharge (Vohra, 1991a). The remaining 40% is the resultant of basal melting and liquid precipitation on the glacier. In extreme cold condition very little water is released by glacier as there is almost no surface melting, whereas basal melt is solely driven by geo-thermal energy and glacier movement. Shape of diurnal, seasonal and annual hydrographs remained unchanged, although discharge showed wide variations year to year.
Discharge measurements were carried out 2km downstream of the glacier terminus at an altitude of about 3800m amsl since 2003 (Figure 4.2). Surface flow velocities were measured by float method and cross checked by current meter periodically. The discharge peaked between 2:00 to 5:00pm and reached a low at around 7:00am on sunny days, with significant differences on rainy or cloudy days. Average discharge of morning, afternoon and evening computed for observation periods during 2003 to 2008 (Figure 4.3) shows that the average discharge varies between 0.5m$^3$s$^{-1}$ to 2.5m$^3$s$^{-1}$ (Sharma, 2007; JNU-IFCPAR, 2009). The average discharge computed for 2009 was 3.92m$^3$s$^{-1}$, with May–June discharge about 10-15% of July–August. The variations observed in discharge and its lag time between the 1980s and 2000s may be due to changes in glaciated area, subsurface channels, ice thickness, meteorological conditions and seasonality.

Figure 4.2 Discharge station re-installed on Chhota Shigri meltwater stream in 2009 (JNU-DST, 2011)
Figure 4.3 Morning, afternoon and evening discharge in Chhota Shigri meltwater stream, 2002-2008 (Sharma et al, 2009)

Meltwater contribution of Chhota Shigri glacier to Chandra river was estimated from discharge data to be 1,14,853 m$^3$d$^{-1}$ in 2003, 1,82,650 m$^3$d$^{-1}$ in 2004, 91,843 m$^3$d$^{-1}$ in 2005, 1,08,864 m$^3$d$^{-1}$ in 2006, 1,02,81 m$^3$d$^{-1}$ in 2007 and 1,13,184 m$^3$d$^{-1}$ in 2008 during the observation period. The average monthly contribution of Chhota Shigri glacier to stream flow for three months (July-September) was 34,45,590 m$^3$ in 2003, 54,79,500 m$^3$ in 2004, 27,55,290 m$^3$ in 2005, 32,65,920 m$^3$ in 2006, 30,84,480 m$^3$ in 2007 and 33,95,520 m$^3$ in 2008.

The discharge measurements attained a momentum in 2010, when automatic level gauge was installed at the discharge site, thus enabling continuous measurements. Depth-integrated velocities were measured by current meter in May and later up-dated with surface velocities at higher water levels.
Figure 4.4 gives the daily averaged discharge hydrograph for the 2010 field season. It was observed that average daily discharges varied from 1 m$^3$s$^{-1}$ in end-May to 8.5 m$^3$s$^{-1}$ in end-July/early August and again reduced to near zero values in early October. Diurnally the discharge peaked between 3.00 to 4:00pm and reached a low at around 7:00am on every sunny day, with significant differences on rainy or cloudy days. Air temperature, driven by solar radiation appears to be the main factor controlling meltwater discharge. The discharge reduced on rainy days, possibly because of lower air temperatures reducing meltwater generation, the exceptions being heavy storm events where the contribution from precipitation compensated for reduced melt. A detailed analysis of diurnal discharge variations to understand the dynamics of the glacier hydrological system is underway as part of the ongoing DST project on Chhota Shigri Glacier.

4.1.1 Discharge – mass balance relationship

The discharge measurements between 2003 and 2008 were carried out in conjunction with annual mass balance measurements for the glacier. A plot of the average discharge and annual mass balance revealed an inverse relationship with discharge (Figure 4.5). The least discharge was observed in 2005 which showed a positive mass balance probably due to heavy snow fall increasing the albedo and reducing snow and ice melt. On the other hand, 2004 with high ablation on glacier surface resulted in increased discharge. This suggests that glacier
melt controls the hydrology of this catchment. However these relationships being based on discharge measurements for short periods have limitations in forming definite conclusions. It is hoped that with the ongoing continuous discharge measurements, discharge-mass balance relationships can be better understood and the hydrological balance computed annually for this representative glacier in Western Himalaya.

![Figure 4.5 Variations of Discharge and Mass Balance 2003-2008 (Sharma et al, 2009)](image)

**Figure 4.5** Variations of Discharge and Mass Balance 2003-2008 (*Sharma et al, 2009*)

### 4.2 Sediment Load

Sediment load of Chhota Shigri meltwater stream was estimated by CWC during August-September, 1989. Average sediment load carried by this stream in the month of August was 529td⁻¹, while average discharge was 9.0m³s⁻¹. The sediment load fluctuated on a day to day basis, increasing with discharge and liquid precipitation (Vohra, 1991b).

Observations made in 1987 and 1988 reveals that the sediment transport characteristics of the melt stream fluctuate widely from 103-2040 ppm (*NIH, 1991*). A drastically high concentration observed on the first day of high peak of discharge is possibly due to side wash load stored in moraines, debris and other alluvial fills. There is no direct relationship between discharge and sediment transport, though broadly it could be stated that an increase in discharge corresponds to increase in suspended sediment concentration (Figure 4.6). In addition a sharp increase in sediment concentration soon after rainfall events was also observed. (Vohra, 1991b).
Figure 4.6 Variation of Discharge and Sediment load in August-September 1989 (Vohra, 1991b)

Table 4.1 gives estimates of average discharge and sediment load for 1987-1989. For a similar discharge in August, the sediment load is lesser than that in July, evidently due to sediment evacuation. Sediment yields reduced drastically in September when the discharge reduced by about 50%. Sediment yield by Chhota Shigri glacier stream was reported to be about 529td\(^1\) during August 1989 and the annual suspended sediment yield from this glacier stream has been computed to be 49,273 tons. The average annual denudation rate in this small 45km\(^2\) drainage basin was approximately 0.766mmyr\(^{-1}\), five times the world average. This high rate of denudation can be attributed to mass movement on steep valley slopes which are mostly un-vegetated and hence easily eroded (Vohra, 1991b).
Table 4.1 Estimated Runoff and sediment load of Chhota Shigri glacier, 1987-1989 (Vohra, 1991b)

<table>
<thead>
<tr>
<th>Month</th>
<th>Average Runoff</th>
<th>Average Sediment load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Discharge m³s⁻¹</td>
<td>Runoff mmd⁻¹*</td>
</tr>
<tr>
<td>July</td>
<td>9.14</td>
<td>17.54</td>
</tr>
<tr>
<td>August</td>
<td>9.28</td>
<td>17.81</td>
</tr>
<tr>
<td>September</td>
<td>5.40</td>
<td>10.37</td>
</tr>
<tr>
<td>Yearly Average (Extrapolated)</td>
<td>3.30</td>
<td>6.33</td>
</tr>
</tbody>
</table>

*millimetres per day

A recent study on the sediment transfer processes during 2003 to 2008 in the glacier meltwater stream observed that sediment load is highest at peak discharge (Sharma, 2007; JNU-IFCPAR, 2009). However, solute concentration decreased with increasing discharges possibly due to dilution effect. Mean solute load during 2005 (minimum discharge year) was only 10% of the mean sediment load while in 2004 (maximum discharge year) it was even less than 10%. The average suspended sediment yield for Chhota Shigri catchment in a day was estimated to be about 4tkm⁻² in 2005, 2006, 2007 and about 6tkm⁻² in 2003 and 2008 while it was 9.5tkm⁻² in 2004 (Sharma, 2007; JNU-IFCPAR, 2009). The average suspended sediment yield for Chhota Shigri stream, for whole melt season was estimated to be about 600-950tkm⁻² during the observation period 2003-2008. Diurnal variability in suspended sediment in this meltwater stream is significantly higher than discharge variation, possibly because sediment is flushed out as the discharges rise during the day and later for the same discharge less sediment is available.
During the 2010 ablation season, suspended sediment concentration varied from near zero to about 3 g/l, increasing as discharges peaked (Figure 4.7). Diurnal variations were equally significant to that of seasonal fluctuations. A wide range of suspended loads were observed for similar discharges, indicating subglacial sediment storage and evacuation. Such wide variations also call for detailed investigations into the dynamics of glacial hydrological system.

Figure 4.7 Suspended sediment concentration in Chhota Shigri meltwater, 2010 (JNU-DST, 2011)
Highlights

Decadal discharges observed during 1986-1989 were significantly higher in comparison to that observed during 2003-2008. The higher discharge observed in the previous decades is comparable with the continuous measurements carried out throughout the ablation season in 2009 and 2010. The factors controlling the inverse relationship observed between mass balance and discharge need detailed investigations.

The discharge and lag time variations observed in the past three decades can be explained by the changes in glaciated area, ice thickness, subglacial hydrology, seasonality, etc. Further attempts are needed to delineate exactly the various factors controlling the lag time using advanced techniques like tracers: fluorescent dye or radioactive isotopes.

Variation in discharge and suspended load shows significant diurnal and seasonal variations even though observed for short periods, which calls for detailed investigations. The average annual denudation rate of this glacier was estimated to be approximately 0.766mm yr\(^{-1}\).
5. Miscellaneous Research

This chapter covers studies carried out in Chhota Shigri Glacier not covered in the previous sections of this status document. These are grouped under palynological studies, spectral reflectance studies, geophysical and geodetic investigations and base metal surveys. Though these studies are of diverse nature, they highlight the other possible approaches through which the glacier environment can be understood.

5.1 Palynological Studies

Palynological studies carried out on Chhota Shigri glacier were initially aimed at obtaining basic information on palynomorphs, their differential production, dispersion and preservation (Bera, 1988). This attempted to correlate pollen spectra and vegetation in the glacier basin through pollen analysis and a pollen deposition model was developed. These studies portrayed the rich pollen assemblage especially conifers in the air catches and surface samples whereas the samples taken from ice core were found to be relatively poor in pollen and spore contents. The study highlights the dominance of extra-regional pollen belonging to conifers along with other broad leaved elements that drifted from low altitude like alpine/subalpine and temperate zones. Furthermore, the pollen analyses of ice core samples reflect that the surface sediments are dominated with pollen and spores and thereafter decrease with the increase in depth. The diatoms encountered in moraines as well as ice cores are of fresh water origin. Fungal spores are also recovered in almost all samples.

Later on snow, firn, ice moraine and atmospheric catches were also subjected to quantitative and qualitative analyses employing absolute and relative frequency techniques (Bera, 1989). The high frequency of conifer pollens in the surface samples and air catches, contrary to the vegetation in the glacier area, are an outcome of pollen interplay from down below. The data obtained from the palynological studies proved to be of paramount importance to reconstruct palaeo-vegetational and palaeo-climatic successions in the alpine and glacier zones during sub-recent period. The study reflects predominance of extra regional arboreals over local non-arboreal pollen taxa. This feature could be due to the transportation of pollen from lower elevation to the tree line zone through upthermic winds. Fluctuations in the values of nonarboreals could be taken as reference to decipher the microclimate changes, whereas the arboreal pollen taxa give indication of the macroclimate of the region.
5.2 Spectral Reflectance Studies

Himalayan Glaciers and snow fields exist in remote and inaccessible areas and locations. Most of the time, the high passes leading to these areas are blocked due to heavy snow fall so the availability of satellite remote sensing imagery for such areas is of immense value for identifying snow and glacier features. Spectral reflectance patterns of the various features of Chhota Shigri glacier were studied using seven band radiometer in visible and near infrared range (Dhanju, 1988; Kulkarni & Dhanju, 1988; Kulkarni, 1989) to aid in identifying these features on satellite imagery. It was found that the ablation zone has about 40% reflectance as compared to the winter snow. The highest spectral reflectance of fresh snow which is debris free has a value of about 0.77 in the spectral range between 433 and 640nm. This type of clean snow is only found in the highest reaches of the accumulation and so any loss of information due to sensor saturation will occur only in limited areas. In the lower part of the glacier where dirty snow is present, the value is half of that of clean snow (Kulkarni & Dhanju, 1988). The features identified were maximum glacier height, equilibrium line altitude, snout height, the glacier length, its average gradient and orientation and the river system into which its melt water drains. The study concluded that the satellite remote sensing within the dynamic range of sensors can discriminate glacier features like clean snow and dirty ice.

5.3 Geophysical Investigations

In 1986, an attempt was made to theoretically calculate the ice thickness of the glacier by generating and interpreting the geophysical potential fields (Bouguer Anomalies) giving an ice overburden thickness of 92-166m for Chhota Shigri glacier (Kumar et al., 1987). In 1987, Geophysical investigations were done to study glacier dynamics in Chhota Shigri Glacier using a La Costa and Romberg Gravimeter Model ‘D’. Gravity observations were carried out with 34 gravity stations of which 24 were established on the glacier. All the gravity stations were linked with the top of a huge granitic boulder at glacier base camp. Gravity survey indicates that the glacier is comparatively thicker on the western side in comparison to the middle part. The maximum thickness of the glacier on the western side can again be well correlated with the maximum strain rate on this side. This infers that the glacier valley is much more inclined or deeper on the western side. High values observed for the ratio of basal velocity and surface velocity in the ablation area indicates that basal sliding is the major mechanism for glacier movement in the NNW direction (Purohit et al., 1988).
Ice thickness calculations indicated an increase from snout towards accumulation zone of the glacier, while maintaining near uniform thickness across the width. The change in thickness of ice is rapid in snout zone, gradual in ablation but very gentle in accumulation zone. Though ice thickness in 1987 was found to be greater than in 1986, the magnitude of change in thickness can only be correctly estimated by repeat observation in future after a considerable gap. The bed rock topography under Chhota Shigri glacier closely paralleled the surface topography. The glacier bed in the mid ablation and snout zones appears to be deeper near its centre than at the margins, possibly due to the narrowness of the glacier valley and the accelerated bed rock erosion near the centre than at the margins due to the differential movement of the glacier. The glacier bed in lower and mid accumulation dips gradually from North towards South, but maintains uniform level across the width of the glacier, probably due to the wide valley with low gradient giving the glacier sufficient space to expand sideward and the hard bedrock minimising basal erosion.

Ground Penetrating Radar (GPR) measurements on Chhota Shigri glacier were carried out in October 2009 in order to calculate the ice fluxes at different cross sections, the bedrock topography of the glacier and ultimately the steady state of Chhota Shigri glacier (JNU-IFCPAR, 2010; Azam, 2010). In order to serve this purpose, few cross sections from lower ablation zone (4400m asl) to higher ablation zone (4900m asl) of the glacier were selected and GPR profiling carried out using Common Offset Radar Survey with concurrent Differential GPS measurements. The present survey was done at a frequency of 4.2-4.5MHz with antenna length of 20m. Transmitter and receiver were separated by a fixed distance of 20m and moved together along the profiles with a step size of 10m.

The cross sections obtained from GPR measurements reveal a deep valley with maximum ice thickness higher than 250 m. The ice thickness (at central line of glacier) increases from 124 m at 4400 m a.s.l. to 270 m at 4900 m a.s.l., and is significantly different from that obtained from gravimetric methods (Dobhal et al., 1995). Even though several cross sections were surveyed for ice thickness by gravimetric method in 1987-88, they were restricted to the lower ablation zone, whereas in the recent study by single frequency GPR the upper ablation zone was also covered. Also the technologies used were different and the surveys were of preliminary nature. Hence detailed ice thickness measurements on the glacier are needed using multifrequency GPR technology.
5.4 Geodetic Investigations

Geodetic investigations were carried out by Survey of India during 1986 and 1987 with the help of control points established in the valley (Bahuguna, 1987, 1988). The average rate of horizontal movement per year in snout region was found to be only 3.7 m/yr and was attributed to the rapid melting rate near the terminus (6.5 cm/yr in July-August 1987). The average rate of horizontal movement per year, in lower, middle and upper portion of ablation zone was 20.4 m, 32.6 m and 42.8 m respectively, higher than the rate of movement in snout zone, but less than in accumulation zone (54 m/yr). The thickness of ice and the gradient or general slope at the base of glacier play an important role in the movement. The rate of horizontal movement per year on glacier points CP-12, CP-14 and CP-16 (Figure 5.1) located on eastern lateral moraine near east margin is 12.5 m, 17.10 m and 21.13 m whereas this movement per year on glacier points GP-7, GP-8 and GP-9 located in the central portion is 14.41 m, 21.67 m and 23.98 m respectively. This is because the central portion of glacier experiences retarding friction only from the ground below but on the lateral regions there is friction from both the sides as well as from the base.

The direction of horizontal movement is NNE except at some points where it is NNW. The trend of rise in height above mean sea level from 0.05 m to 0.95 m, in the case of all glacier points in snout zone gives a clear indication of advancement in the glacier surface level. The trend in ablation zone shows that the magnitude of decrease in height of each glacier point is not in proportion to the appreciable magnitude of downward horizontal movement indicating the overall rise in glacier surface level in ablation zone.
Figure 5.1 Planimetric control in Chhota Shigri glacier area during 1987, showing locations of control points (CP) and glacier points (GP) (Bahuguna, 1988).
Fluctuations were found in the width across the glacier at few places in snout and ablation zones. The retreat in relative depths of glacier surface level just along the east margin as compared to the fixed and stable rocks on side hills near and below the points CP-16, CP-18 and GP-28, has indicated rise of the order of about 0.5m to 0.8m. Similarly, the glacier surface level just along west margins near and below the points CP-15, CP-17, CP-19 and CP-21 rose by about 0.7 to 0.35m since September, 1986. The rate of fluctuation in glacier surface level in ablation zone was higher along the west margin than along the east margin. The width of lateral moraines along the east and west margins was found advancing inward by about 5 to 7m in the lower and middle portions of ablation, where as this advance in upper ablation zone was 2 to 3m only. The marginal increase in relative heights of the lateral moraines along the east and west margins, throughout in ablation zone was also noticed. The repeatedly measured width of the rims of few prominent crevasses over the glacier surface in accumulation zone and upper ablation zone, within the interval of 5 to 10 days, were found to increase by about 10 to 25cm.

5.5 Investigation for Base Metal Minerals

The moraines were studied by the Geological Wing, Department of Industries, Himachal Pradesh with special reference to minerals of base metals (Katoch, 1989). Sampling from debris of moraines was carried out from the confluence of Chhota Shigri meltwater stream and Chandra River to a height of 4700 m. Chalcoprytite found in the lateral moraines were followed upstream, and were traceable upto the height of 4700 meters, but could not be followed above this point due to heavy crevasses in the ice. The quantities found in the moraines do not indicate any major deposit, but thin veins of this mineral can be expected. The morainic debris between Chhota Shigri and Bara Shigri streams lying parallel to the Chandra River was also sampled and some samples of stibnite ore were found associated with lead and zinc. This mineralization is entirely in the granitic rock and is localized along fractures and fracture zones that cut these rocks; the mineralization appears to be in the form of cavity filling deposit of hydrothermal origin. Most of the veins dip at 60° to 90° with major strike being NNE-SSW. The mineralization is restricted to three elevations between 4250 to 4650 meters and each is separated by banded quartzite-sericite schist. These veins are variably rich in different metallic sulphides along the fracture. Stibnite veins along fractures trends 10° N to 40° E and occurs as radiating crystals. The veins become thin and even disappear when fracture becomes straight. The veins are well defined and their contact with
the wall is clear. Detailed investigation of the stibnite deposit needs to be carried out to find out its economic viability.

**Highlights**

Palynological studies show transportation of conifer pollen from lower elevations to the Chhota Shigri glacier catchment by upthermic winds.

Spectral reflectance surveys on Chhota Shigri glacier suggest that it is ideally suited to delineate glacier morphologic features for field-truthing of remote Sensing observations.

Geodetic investigations indicate that bed rock topography of Chhota Shigri glacier parallels the ice surface topography.

Geophysical investigations revealed that maximum ice thickness is well correlated with the maximum strain rate. Recent ice thickness measurements are significantly higher than earlier estimates possibly due to difference in techniques adopted.

Traces of chalcopyrite and deposits of stibnite were found in a mineralogical investigation of the lateral moraines.
6. Summary and Conclusions

The preceding chapters of this status report focused on various aspects viz. morphology, climate regime, snout fluctuations, mass balance, surface velocity, hydrochemistry, hydrology, ice thickness, palynology, etc. of Chhota Shigri glacier in the Lahaul-Spiti valley of Himachal Pradesh, India - a ‘bench mark’ glacier chosen by UNESCO/ICSI in 2002 and identified by DST as one of the representative glaciers for long term integrated monitoring.

6.1 Current status of research on Chhota Shigri

Chhota Shigri glacier, a 9km long, 15.7km² valley-type glacier located between 32.19° N to 32.28° N and 77.49° E to 77.55° E lies in a 37.7km² catchment of which only 47% is glacierised. The terminus of the glacier is at an elevation of 4050m amsl while the maximum elevation is 6263m amsl. The entire glacier valley shows well-developed morphologic features such as moraines, crevasses, glacier till, cirques, glacier tables, snow-clad peaks, truncated spurs with snow-off faces, hanging valleys, conical and pyramidal peaks, water channels and screed flows. The medial moraine is represented by prominent uplifted glacier surfaces that demarcate two ice streams: one coming from the eastern flank and the other from the western flank. The lower ablation zone of the Chhota Shigri glacier is covered by surface moraine and debris. Transverse crevasses are distributed all over the glacier, running almost at right angles to the length of the glacier in E-W direction, whereas longitudinal crevasses are mainly found in the lower part and sides of the glacier valley, while radial and marginal crevasses are recognized near the snout of the glacier.

The climate of Chhota Shigri and its adjoining area is typical of monsoon-arid transition zone where both the summer Asian monsoon and the winter mid-latitude westerlies influence the precipitation regime. The Chandra River valley where the glacier is situated is drier than the southern slopes of the Pir Panjal range. This is the leeward effect of the main ridge mostly oriented W-E preventing part of the monsoon flux from reaching the valley. The precipitation ranges from 150 to 200cm with lower reaches of the glacier falling in the cold dry valley.

Very limited meteorological data is available for Chhota Shigri glacier and only for short spells ranging from one week to few weeks at a time. A positive step towards in situ climate data collection on this bench-mark glacier was accomplished in 2009, when an Automatic Weather Station was installed at about 4920m amsl. The daily maximum temperature observed was about 11.8°C and 19.6°C, while minimum temperature was -13.6°C and 0.1°C on glacier surface and below the glacier terminus respectively. Relative humidity varied
between 12-99% over the glacier surface.

Lithology of Chhota Shigri glacier valley is dominated by the Central Crystallines, with the crystalline axis comprised mostly of meso- to ketazonal metamorphites, migmatites and gneisses. Traces of Chalcopyrite was found in the lateral moraines, while Stibnite associated with lead and zinc mineralization was found in the granitic rock. Snout position of the Chhota Shigri has been monitored periodically from 1962 (Survey of India Toposheet of No. 52H/11 & 12), with observations made in 1984 and 1995. Past positions demarcated by studying the morainic streaks indicate six morainic loops which not only reflect the retreat of the glacier snout but also past advances.

Mass balance studies in the Chhota Shigri glacier were carried out in two phases: Phase I in the 1986-1989 and Phase II from 2002 onwards. The summer net balance obtained in 1987 and 1988 were similar while the cumulative specific balance for 1986-1989 was -0.21m weq. The specific mass balances during 2002-2008 were mostly negative varying from –1.4m weq (2002/2003 and 2005/2006) to + 0.10 m weq in 2004/2005. Debris cover, orientation and shading effect of valley slopes were found to be major factors influencing the rate of ablation on the glacier. Annual mean surface velocity on the Chhota Shigri glacier between 1985 and 1988 was found to be 32.60myr⁻¹, 41.29myr⁻¹ and 37.21myr⁻¹ respectively, while between 2003 and 2007 it was 38.5myr⁻¹, 37myr⁻¹, 36myr⁻¹ and 37.5myr⁻¹ respectively. Although separated by almost two decades, the results from the two studies show no significant change in the surfacial velocity pattern of the Chhota Shigri glacier.

Energy balance of the glacier was attempted using three observatories at different altitudes on the glacier and by dividing the glacier into four altitudinal zones with an altitude interval of 400m. It was found that the albedo values in the ablation zone ranged from 10 – 20% for the glacier ice and 42% for the firn. In the accumulation area due to fresh snow the albedo values were found to be high and the contribution from insolation was fairly low and almost negated by net longwave radiation and latent heat flux, resulting in nil effective melting.

The concentrations of the major ions measured in snow and a shallow ice core indicated predominantly marine origin of Na⁺ and Cl⁻, while K⁺ and Ca +++ were mainly derived from terrestrial sources whereas Mg ++ contributions came from both marine and terrestrial sources. The available data of melt water chemistry mostly are restricted to July-August and September. It was observed that supraglacial water has lower concentration of solutes compared to glacier melt water that comes out of the glacier terminus indicating the
intermixing of supraglacial and subglacial waters to form solute enriched portal meltwaters. Meltwaters flowing through subglacial channels become chemically enriched probably by interacting with basal morainic material.

Using a half-life value of 140 years for $^{32}\text{Si}$ and assuming the average value of $^{32}\text{Si}$ concentration in the snow precipitation in the Himalayan region to be 0.7dpm$10^3\text{l}^{-1}$, a radiometric age of 250 years of snout ice was obtained and the average surface ice flow rate over the past few centuries was calculated to be 28myr$^{-1}$. Using measured $^{32}\text{Si}$ concentration in the melt water, the radiometric age of the average melt water has been estimated to be 80 years. This suggests that a mix of at least 55% snow melt and 45% ice melt emerges from the Chhota Shigri glacier terminus. Based on $\delta^{18}\text{O}$ variations in a shallow ice core, the snow accumulation on Chhota Shigri glacier, averaged for the 2 years prior to August 1987 was calculated as 520kgm$^{-2}\text{yr}^{-1}$.

High and low melt water stream discharges ($Q_H$ and $Q_L$) occurred between 1530-1900 hrs and 0300-0700 hrs respectively, with daily mean discharges ranging from 6 to 13m$^3\text{s}^{-1}$ and $Q_H:Q_L$ at about 1.50. High discharges were observed during night because of the melt storage characteristics of the glacier; the lag time to the gauging site was estimated at 1-2 hours in 1988 and at 2-3 hours in 1989. Discharge varies directly with temperature and it can explain about 60% of discharge. Mass balance can help understand the discharge variation, which was a minimum in 2005 when the Chhota Shigri glacier showed a slightly positive mass balance, while in 2009 a negative mass balance year, it more than doubled from previous years, suggesting that glacier melt controls the hydrology of this catchment. In general, the sediment load increases with discharge. However, no direct relationship could be established between discharge and sediment transport. Sediment yield of Chhota Shigri glacier stream was about $529\text{td}^{-1}$ during August, showing very high denudation rates. The average suspended sediment yield in a day was estimated to be about $4\text{tkm}^{-2}$ in 2005, 2006 and 2007, and about $6\text{tkm}^{-2}$ in 2003 and 2008 while it was about $9.5\text{tkm}^{-2}$ in 2004. This high rate of denudation could be attributed to tectonics and mass movements on steep bare slopes. While fine sediments dominated the peak load, the falling limb of the seasonal hydrograph showed increased medium and coarser fraction, pointing to lack of supply of fine sediments.

A non-linear empirical model for the computation of snow and ice melt runoff as a function of temperature, net solar radiation and albedo was attempted. The observed values of these parameters for peak ablation period were fitted and a non-linear regression analysis was performed between observed discharge and meteorological parameters.
Palynological studies of ice and surrounding surface materials portrayed a rich pollen assemblage of conifers in the air catches and surface samples whereas ice core samples were relatively poorer in pollen and spore contents. The study shows the dominance of extra regional pollen belonging to conifers along with other broad leaved elements probably resulting from transportation of pollen from lower elevation to the tree line zone through upthermic winds.

Spectral reflectance studies using a seven band radiometer in visible and near infrared range showed that the ablation zone has about 40% reflectance as compared to the winter snow. An attempt was also made to identify various features like snow, ice, debris covered ice, streams, rocky areas, etc. using spectral reflectance characteristics. AAR also was calculated on the basis of identifying the snow line.

Strain measurements showed a thinning of the glacier in the middle in the 1980s. Gravity observations showed that the ice thickness significantly increases from North to South, i.e. from snout to accumulation zone, though fairly uniform across the width of the glacier. The melting at the snout is highest and this leads to glacier movement. The average rate of horizontal movement per year, in lower, middle and upper ablation zones is 20.4m, 32.6m and 42.8m respectively, increasing further in the accumulation zone. However, bed-rock surface erosion by glacier movement might be more pronounced near the centre than at the margins due to the differential movement of the glacier.

Ongoing research on this benchmark glacier begun in 2002 initially focused on annual mass balance monitoring and has lately been augmented with winter mass balance studies, apart from periodic ice surface velocity and meltwater discharge measurements. Energy and hydrological balances, hydrochemical studies and a preliminary attempt at glacier ice thickness are being carried out at the moment.

### 6.2 Limitations and gaps

A large volume of multi-disciplinary data has been generated over the last three decades on Chhota Shigri glacier. However, there is need to exercise caution while using some of these data as the methodologies, technology and understanding of glacier dynamics have changed over time and because of the short duration of observations warranted by the expedition mode in which many of these were carried out. For example, the annual terminus retreat rates obtained from various studies show significant differences in the retreat pattern ranging from 5.9myr$^{-1}$ (GSI) to 53.3myr$^{-1}$ for various time periods within the last 50 years. Mass balance
monitoring in the 1980s had two limitations viz. the exclusion of tributary glaciers and the inability of metallic stakes drilled 2.0-2.5m into the glacier ice to reveal the upper limit of annual ablation. Although the glacier is reported to have undergone negative balance conditions during both the observation periods, the glacier area reported in the studies of 1980s is significantly smaller than that mapped by remote sensing methods in 2000s. The terminus positions and aerial extent was compared on repeat imageries between 1972 and 2006. Average terminus retreat of 25myr\(^{-1}\) was inferred, along with loss of glaciated area of about 19.5%. Another study showed a larger glaciated area of 16.5km\(^2\) in 2005. This difference can be attributed to the earlier studies that were restricted to the main glacier tongue and raises problems for inter-comparison of data sets.

During 1987, 1988 and 1989 ELA was found to be 4650m, 4700m and 4840m respectively with corresponding AAR value of 73%, 59% and 65% respectively. The ELA for 2002/2003, 2003/2004, 2004/2005, 2005/2006, 2006/2007, 2007/2008, 2008/2009 and 2009/2010 was found to be 5170m, 5165m, 4855m, 5185m, 5150m, 5120m, 4980m and 4930m respectively with corresponding AAR value of 31%, 31%, 74%, 29%, 34%, 47%, 63% and 70% respectively.

Scarcity of meteorological data for the Chhota Shigri glacier basin is a limitation in establishing definite climate-discharge relationships. Available data is also insufficient to arrive at definitive conclusions regarding variability in the chemical behavior of Chhota Shigri glacier. The studies spanning more than two decades suggest a very high variability in solute concentration over years and seasons. Most of this variability could be explained in terms of dilution effect because the sampling times were different in various studies. But even when the samples were for comparable time periods, there are wide variations which can be explained by differing climatic conditions at the sampling time or limitations of different methodologies adopted for analysis.

In addition to the above-mentioned limitations, there are a few gap areas that need to be addressed to further the understanding of climate-glacier-lithosphere interactions on this benchmark glacier. Some of these pertain to reconstruction of palaeo-climate and palaeo-glaciation interactions during the Quaternary, the influence of atmospheric brown cloud and black carbon on glacier melt/recession, quantifying the relative influence of Asian monsoon and western disturbances on precipitation and accumulation, mapping the glacier hydrological system and the characterization of ecological systems that correspond to various extreme physical environments prevalent on this glacier.
6.3 Prospects for future research

In light of the current status of research and the gaps and limitations that exist, a few focal areas are suggested to carry forward the research thrust to its logical conclusion. The first of these is to gain an understanding of the microclimate of the Chhota Shigri glacier and how the exchange of mass and energy between glacier surface and atmosphere actually works. The glacier boundary layer plays an important role in controlling the dynamics and health of a glacier. The knowledge of the micro-meteorological processes on a network of index glaciers including Chhota Shigri, Hamta, Patseo among others will ultimately make it possible to develop mass balance models for the Western Himalaya. With these models the sensitivity of the balance rate to climate change can be studied. In the light of global climatic changes bringing about possible change in glacier hydrological systems, there is urgent need of multi-seasonal long term monitoring of chemical parameters of glacial ice, snow and melt-waters that need to be corroborated with glacial sediment chemistry.

The supraglacial, englacial and subglacial environments may differ vastly in terms of their water content, nutrient abundance, redox potential, ionic strength, rock-water contact, pressure, solar radiation and pH conditions. This remarkable physical diversity means that glaciers provide an ideal opportunity to draw the ecologies of ice in all its forms into one single field-scale system. This potential need to be tapped with a glacier-scale perspective of the physical, biogeochemical and microbiological characteristics of glacial ecosystems.

Apart from the above foci of research, the source and age determination of glacier ice and portal melt waters, subglacial hydrology, delineation of internal structures, base rock topography and estimation of ice volume through detailed multi-frequency GPR surveys, investigation into the thermal structure of glacier ice, impact of aerosols and black carbon on glacier, palaeo-climatic investigations, glaciological modelling, etc. need to be taken up for strengthening the long-term integrated monitoring of this bench mark glacier on the monsoon-arid transition zone of the Indian Himalaya. These studies require a multi-disciplinary approach and needs inputs and involvement of specialists from diverse fields of research. It is hoped that this status report will motivate institutions and specialized research teams to join hands to make this cherished goal a reality.
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<td>Director</td>
<td>Wadia Institute of Himalayan Geology, Dehradun</td>
<td>Member</td>
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<td>13</td>
<td>Representative</td>
<td>of the Ministry of Earth Science, New Delhi</td>
<td>Member</td>
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<td>Dr. M. Prithviraj</td>
<td>SERC, Department of Science &amp; Technology, New Delhi</td>
<td>Member Secretary</td>
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<td>15</td>
<td>Dr. P. Sanjeeva Rao</td>
<td>SERC, Department of Science &amp; Technology, New Delhi</td>
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