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Degradation of Siachen Glacier in the Context of Volumetric Decrease in Siachen, Baltoro and Biafo Glaciers of Pakistan

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ABSTRACT: The glaciers of the Hindukush-Karakoram-Himalayan (HKH) region consist of a huge amount of perpetual snow and ice. These glaciers are retreating in the face of accelerating global warming. Estimation of volumetric decrease of Siachen glacier out of Shyok river basin and that of Baltoro and Biafo Glaciers out of Shiger river basin is carried out in this study using Remote sensing satellite and Topographic data.

The total geographic area of the river basins in northern areas is about 128,730 km2. Altogether, 5,218 large and small glaciers in northern areas cover a total glaciated area of about 15,040 km2. The total ice reserves in HKH region of Pakistan are about 2,738 km3. The Hunza, Shyok and Shigar basins contain the major part (about 83%) of these ice reserves.

Alpine glaciers are subjected to volumetric decrease owing to host of factors. This study presents the volumetric decrease computations during the decade of 1990-2000 of largest glaciers of northern areas of Pakistan. The results computed through study are there after compared with mathematical model of ice reserves and ice thickness which supplements their validity. Finally the correlation of volumetric decrease of these glaciers with average temperature rise of northern areas and sea level rise along coastline of Pakistan during the last decade is carried out.

The percentage volumetric decrease of Siachen, Baltoro and Biafo and glaciers during the decade, computed in this study work, subjected to manifest of global warming and anthropogenic activities indicates that three out of world's seven largest glaciers have experienced a volume loss of 11.09, 6.14% and 3.79% respectively during the decade of 1990-2000.

KEYWORDS: Siachen Glacier, Volumetric Decrease, Baltoro and Biafo Glaciers, Pakistan.

1 INTRODUCTION

The glaciers are nature's renewable storehouse of fresh water that benefits hundreds of millions of people downstream. The glaciers of the Hindukush - Karakorum - Himalaya (HKH) region, however, are retreating in the face of accelerated global warming since the second half of the 20th century and have contributed to the formation of many glacial lakes on the recent glacier terminus (Mool et al., 2001). Rapid accumulation of water in these lakes can lead to sudden breaching of the unstable moraine dams discharging huge amounts of water and debris causing loss of life, property and the destruction of valuable forest and pasture resources, farmlands, and costly mountain infrastructures downstream. Some glaciers are reported to have created long-term secondary environmental degradation physically and socio-economically, both locally and in neighboring downstream countries (Nurkadilov et al., 1986). Glaciers retreat is recognized to be a common phenomenon in the Hindukush - Himalayan countries such as Bhutan, China, India, Nepal and Pakistan.

A major part of the snow and ice mass of the Pakistan's HKH region is concentrated in the watershed of the Indus basin. This watershed can be divided into distinct river basins. The study is carried out in two river basins of HKH region of the country in two phases. In the first phase the volumetric decrease of Siachen, Baltoro and Biafo glaciers was estimated. In the second phase quantitative correlation with average temperature rise in northern areas and sea surface rise along the coast line of Pakistan during the last decade was analyzed and discussed.

The total geographic area of northern Pakistan is about 128,730 km^2. Altogether 5,218 glaciers were identified which cover a total glaciated area of about 15,040 km^2 (about 11.7% of the total geographic area of the basins). These glaciers contribute total ice reserves of about 2,738 km^3. The Shyok, Shyok and Shigar basins contain the major part (about 83%) of these ice reserves.

Accurate and comprehensive knowledge of glaciers is of utmost importance for water resource management. A digital repository of valuable knowledge on glaciers can enhance the ability to inform policy makers on the vulnerability, risk mitigation and action/adaptation measures. Specifically for Pakistan where irrigation network of the country is heavily dependent on the snow melt in summer, this information on one hand can serve to plan the agricultural activities downstream according to the ice reserves available and the prevailing climate and on the other it can provide a basis for future climate change / global warming studies.

The northern and western parts of Pakistan are mountainous regions, where all the land is in the form of rugged terrain including mountains and hills. Generally, the northern mountainous slopes are steep and the region is vulnerable to landslide and river erosion due to great elevation differences, and fragile geological conditions. In addition, the watersheds of the region are covered by some major glaciers, which are quite susceptible to disastrous outbreak / flooding hazards. In general, snow clad line is found above 5,300 meters above sea level. The glaciers, some of which consist of a huge amount of perpetual snow and ice, are found to retreat at a faster pace than ever during the last 50 years. In Pakistan these glaciers are the sources of the headwaters of Indus River, thus are a precious natural asset for the country.

1.1 GEOMORPHOLOGY

High mountains of Pakistan comprise the western end of 2,400 km long Himalayan range and some parts in the Hindukush and Karakoram ranges stretching over the province of Khyber Pakhtunkhwa and the northern areas. Northern areas spread over 72,496 km^2 with a midst towering snow-clad peaks having heights varying from nearly 1,000 to over 8,000 meters above sea level. OUt of the 14 over 8,000 m peaks on earth, 4 occupy an amphitheater at the head of Baltoro glacier in the Karakoram Range. These are: K-2 (Mount Godwin Austen) which is 8,611 m and is world second highest peak, Gasherbrum-I (8,068 m), Broad Peak (8,047 m) and Gasherbrum II (8,035 m). There is yet another peak which is equally great, that is, Nanga Parbat (8,126 m) at the western most end of the Himalayas and is rated as world's 8th highest peak. In addition to these, there are 68 peaks over 7,000 m and hundreds which are over 6,000 m high. Generally, because of their rugged topography and the rigors of the climate, the northern highlands and the Himalayas to the east have been formidable barriers to movement into Pakistan throughout history. There are though several famous passes like Khyber, Kurrum, Tochi, Gomal, Lowari and Khunjerab, which have been used historically as trade routes.

The northern Pakistan has some of the longest glaciers outside polar region like Siachen (76 km), Hispar (61 km), Biafo (62 km), Baltoro (59 km), Batura (64 km), Yenguta (35 km), Chiantar (34 km), Trich (29 km) and Atrak (28 km). The lower Himalayan valleys of Swat, Kaghan and Chitral in the Hindukush range equally share the beauty and diverse culture of the northern Pakistan. The HKH region in Pakistan house many gorgeous lakes especially like Saif-ul-Maluk, Satpara and Kachura.

The lower mountain ranges in the northeast receive high monsoon rainfall in summer and snow precipitation during winter. The forest cover is dense in this mountain region. The high northern and northwestern areas are out of monsoon reach so the climate is dry and precipitation occurs only due to cyclonic depressions moving in from the west during spring and summer. Three out of seven world's largest glaciers are present in the northern areas of Pakistan making its geographic location prime in the region.

1.2 CLIMATE

Pakistan is basically a dry country of the warm temperate zone. The climate of the area is transitional between that of central Asia and the monsoonal region of south Asia, which varies considerably with latitude, altitude, aspect and local relief. There is not only high spatial variability but temporal variability is quite high as well. Except for a small strip of sub-tropical terrain in Punjab and the wet zone on the southern slopes of the Himalayan and Karakoram mountain ranges, most of the country is arid or semi-arid steppe land.

There are two distinct rainy periods, one in summer and one in winter. The monsoon rainfall is extensive in period from July to September. The winter is dominated by the westerly fronts originating from Mediterranean region. In the north of the country, most of the precipitation is not only derived from the Indian monsoon but from depressions moving in from the west during the spring and summer as well. The winter snow, glaciers and snowfields start melting from April and continue till July when monsoon sets in.

The snowmelt run-off constitutes a substantial part of water resources of the rivers of Pakistan. The Indus River, primarily supplied by glaciers in its upper reaches, and subject to the least seasonal variation, still has a maximum flow more than fifty times its minimum. The Indus basin irrigation network in Pakistan stretches over an area of 14 M ha (Asim et al., 2002). The network has three major reservoirs (Tarbela, Mangla and Chashma), 19 barrages or headworks, 12 link canals and 43 canal commands.

Five main rivers, namely, the Indus, Jhelum, Chenab, Ravi and Sutlej flow through the country's plains. Aided by a number of smaller tributary rivers and streams, these rivers supply water to the entire Indus Basin Irrigation System (IBIS), which forms the world's largest contiguous irrigation system. Alpine glaciers contribute 50 % of the Indus water flow. The Indus River is about 2,800 km long and 62% of its catchment lies in Pakistan (Shafique and Skogerboe, 1984). Indus system receives a number of tributaries from the west: Kabul, Kurram, Tochi and the Gomal Rivers. The eastern tributaries are Jhelum, Ravi and Sutlej. The five major rivers combine at Panjnad. The swelling of Indus and its tributaries is subjected to volumetric decrease of glaciers and if coupled with heavy monsoonal rains, can cause floods during summer.

1.3 HYDROMETEOROLOGY

The hydro meteorological cycle forms a link between two great natural reservoirs, the snow and glaciers in the mountains and the groundwater contained in the aquifers in the plains of Pakistan.

1.3.1 GLACIATED RIVER BASINS OF PAKISTAN

For hydrological studies, Pakistan's northern area is divided into 10 major river basins (Figure 1.1). Clockwise from west, these basins are of Swat River, Chitral River, Gilgit River, Hunza River, Shigar River, Shyok River, Indus River, Shingo River, Astor River, and the Jhelum River. Most of the snow and ice reserves are concentrated in the mountain ranges lying in these basins. These river basins contain glaciated part of northern Pakistan, which forms headwaters of the main Indus basin.

The tributary rivers also have their origin in the Himalayas and derive their flows mainly from snowmelt and monsoon rains. Snowfall at higher altitudes (above 2,500 m) accounts for most of the river runoff. The active hydrological zone lies between 2,500 and 5,500 m, and snowfall in the mountains accounts for a large portion of the total runoff into the river (PSIHP, 1991). Within this zone, snow and glacial melt contribute towards river runoff from March to September. In the upper Indus catchments, the snow line is at an elevation of 5,500 m; above this elevation it's the process of snow accumulation that dominates rather than melting of snow even during the summer months.

Figure 1.1: Glaciated river basins of northern Pakistan, a major source of Indus river outflow in Arabian sea.

The snow and ice melt from the glacial area of the upper Indus catchment supply approximately 80% of the total flow of the Indus River in the summer season. Snowmelt accounts for more than 50% of the flow in the Jhelum River but it is much more dependent than the Indus River for variable monsoon runoff. Since the Chenab River rises at higher altitudes, snowmelt accounts for a considerable proportion of its runoff.

1.3.2 Shyok River Basin

The Shyok River basin actually forms the sub basin of the Gilgit River but due to its considerable size and importance it is considered as a separate basin. The river drains the Karakoram Mountains comprising of large glaciated area in the north.

The Karakoram highway linking Pakistan to China passes across this basin. Part of the road runs along Shyok River and ends near Khunjerab Pass.

The tributaries joining the Shyok River are Chabursan, Khunjerab, Ghujerab, and Shunsha River. The basin comprises of major valleys and hanging glaciers on the high Karakoram Range. Karimabad, the capital of the Shyok valley, is stretched over miles and miles of terraced fields and fruit orchards. It offers a panoramic view of the Rakaposhi, Ultar and Balimo peaks.

Gulmit is shining white and deeply crevassed - just as you would expect a glacier to look. Above this glacier to the left is the jagged line of the Passu and Siachen peaks, seven of which are over 7,500 m. Passu is the setting-off point for climbing expeditions up the Siachen, Passu, Kurk and Lupgar groups of peaks, and for trekking trips up the Shimshal Valley and Siachen Glacier.

1.3.3 SHIGAR RIVER BASIN

Shigar River is a small right bank tributary of the Indus River. This river rises from the Hispar glacier at the base of the Haramosh and Kanjut Sar peaks in Shigar valley. Thereafter it flows towards the southeast and joins the Indus at Skardu. The Shigar River drains parts of Haramosh range and Masherbrum range in the northeast of the country. The river fed by melting water of large glaciers, joins the main Indus River near Skardu. In the east of the basin there is a tributary named Bro River entering into the Shigar River.

An important tributary of the Shigar River rises from the Baltoro glacier at the base of the Masherbrum peak and flows westwards to join the main channel of the Shigar in its middle course. Thus the Shigar system drains the melt-waters of two of the most important glaciers (Baltoro and Biafo) of the Karakoram Range. This river descends along a very steep gradient. Its entire catchment has been influenced by the action of glaciers. The valley is deep in its upper reaches but widens near its mouth. A small river island has formed at the junction of the main stream with the tributary draining the Baltoro glacier. The catchment area of this river is virtually devoid of a vegetative cover due to its high altitude and scarcity of rainfall moreover the human habitation is sparse.

Shigar Valley, 32 km from Skardu is watered by the Shigar River. It forms the gateway to the great mountain peaks of the Karakoram, including K-2.

1.4 OBJECTIVES

The prime objective of this study is to assess the degradation of Siachen glacier in the context of volumetric decrease in Siachen, Baltoro and Biafo glaciers of Pakistan subject to global warming incl anthropogenic activities. The secondary objectives are as following:

- Estimation of three major glaciers depletion during the decade.
- Correlation with sea surface rise along coast line of Pakistan during the decade.
- Correlation with average annual temperature rise in northern areas in a decade.

1.5 SCOPE OF THE STUDY

Indeed, attempt has been made to document the glaciers depletion of northern Pakistan in the past but with traditional survey methods. In recent times, the dynamics of land cover and particularly climatic change in the area requires a more powerful and sophisticated system such as GIS and remote sensing data which provides a general extensive synoptic coverage of large areas than the traditional survey methods. Remote sensing is helpful in providing up-to-date information and GIS assists in marking spatial distributions and its management. Spatial distribution of glaciers depletion is now possible with high spatial, spectral and temporal resolution image giving fairly accurate results. This study deals with,

- Three major glaciers of Siachen, Baltoro and Biafo in northern Pakistan.
- Only volumetric changes during the last decade are estimated.
- RS and meteorological data are used for the subject study.

2 LITERATURE REVIEW

Earth surface is unique in characteristics it possesses in the form of land cover. Intergovernmental Panel on Climate Change (IPCC) in 1988 reported that global warming is the gradual rise of the earth's near-surface temperature over approximately the last hundred years. The best available scientific evidence based on continuous satellite monitoring and data from about 2,000 meteorological stations around the world indicates that globally averaged surface temperatures have warmed by about 0.3 to 0.6°C since the late nineteenth century. Generally, the northern hemisphere has warmed to a greater extent than the southern hemisphere, and mid to high latitudes have generally warmed more than the tropics. Alpine glaciers are subjected to heat flux thus causing them to melt.

Mare (1997) found that the edge of the summer ice moved almost 3 degrees south between the mid-1950s and early 1970s. That's a big shift almost 200 miles enough to reduce the area of the sea ice by 25 percent. Mare's (1997) finding signals an increase in planetary temperature and is an indication that polar ice would shrink if greenhouse gases do warm the planet. Such a precipitous decline in ice area "poses a challenge to model simulations of recent climate change," Mare (1997) wrote, since climatologists have assumed that such changes would be much more gradual. The shrinking of Antarctic ice sheet signals a rise in global temperature (Mare, 1997). Any change in ice distribution could affect ocean circulation. Ocean currents redistribute heat from the tropics to the poles and are a key part of the global climate system.

Titus and Vijay **(**1995) studyed that after the last ice age, the rapid melting of glaciers rapidly raised sea level. That melting tapered off about 6,000 years ago, and sea level compared to land became fairly stable. However, over the past century, sea level over much of the United States has risen by 25 to 30 centimeters relative to land. They concluded that sea level during the last century raised more than average over the last several thousand years (Titus and Vijay, 1995).

The warming of the atmosphere caused by increases in greenhouse gases is melting glaciers and causing ocean water to warm and expand thermally. Both effects increase the volume of the ocean, raising its surface level. How far has the average ocean surface moved from the center of the earth, nobody has made that measurement consistently, so we must settle for records of relative sea level rise, which tells us about sea level rise in comparison to a certain hunk of coastal real estate.

Crests of the high ranges in the Karakoram–Himalayan region are largely snow bound. The Karakoram has greater ice and snow cover (27 to 37%) than any other mountain system outside the polar region (Wissman, 1959). In Hindukush, western Karakoram and high Himalaya, ice and snow cover is relatively less extensive, and in other ranges west of Nanga Parbat only the highest peaks are snow bound. Snow line is at about 5,200 masl to 5,800 masl along the northern aspects of the high Himalaya. It is at 5,100 masl to 5,600 masl in southern Karakoram and 4,700 masl to 5,300 masl in the northern part of the Karakoram (Kick, 1964).

2.1 GLACIOLOGICAL COMPLEX

The Karakoram-Himalayan region lies in an environment that is glaciological complex with high altitude source areas (above 4,500 m) having permafrost and annual precipitation in excess of 2,000 mm (Khan, 1994).

The Karakoram alpine glaciers are amongst the steepest in the world and they extend through a wide range of climatic environments. Most of the precipitation is not derived from the Indian monsoon but from depressions moving in from the west during the spring and summer. However, occasional monsoon disturbances do succeed in extending sufficiently far north so as to enter the area. Under such circumstances the precipitation levels increases substantially.

2.1.1 GLACIER'S VELOCITY AND FLUCTUATIONS

Due to great thickness of ice, the deeper parts of the glaciers are at or close to 0 °C and they behave like temperate glaciers (Hewitt, 1998). Owing to relatively high activity indices, these glaciers have relatively high flow rates ranging from 100 to 1,000 m/yr (Goudie et al., 1984). Velocities of some of the selected glaciers of Karakoram are shown in Table 2.1. Historical record of glacier fluctuations in the Himalayas and the Karakoram indicate that in the late nineteenth century the glaciers were generally advancing followed by predominant retreat (Goudie et al., 1984).

High summer radiation and steep barren slopes control the glacier ablation patterns. It is estimated that melting accounts for 80% of the heat loss whereas only 20% is due to evaporation and convection (Goudie et al., 1984).

Table 2.1: Published estimated lengths and velocities of Siachen, Baltoro and Biafo glaciers. The length data is of year 1998 and the velocities are yearly average (Hewitt, 1998).

Glaciers	Length (km)	Velocity (m/yr)
Siachen	76	1,000
Baltoro	59	300
Biafo	62	19

There are episodes of rapid advances and catastrophic movements occasionally observed in alpine type of glaciers subject to global warming. Hewitt (1998) observed catastrophic movement of 16-km-long Chiring glacier (Indian Himalayans) between 1994 and 1996, which transferred 1-1.5 km^3 of ice from its upper two-third to its lower one-third, and into the main Panmah glacier of which it is a tributary.

2.1.2 GLACIAL SURGES AND CLIMATE CHANGE

Five confirmed and three other possible glacial surges in Karakoram have occurred in the past decade (Hewitt, 1998), possibly indicating sensitive response to climate change. The Karakoram lie within the variable influence of three major weather systems: the sub-Mediterranean regime of mainly winter, westerly storms; the summer monsoon; and the Tibetan anticyclone. Winter storms dominate glacier nourishment at present. However, nearly one third of the high-elevation snow accumulation which has been measured occurs in summer (Hewitt, 1990). Moreover the general patterns of advance and retreat in the region relate to changing vigor of the summer monsoon. The possibility of such large shifts in the atmospheric sources, regime, and seasonal occurrence of glacier nourishment, does not seem to be a factor in other regions with surging glaciers. This seems to be a further reason to give more attention to surging glaciers in a relatively neglected region as the glaciers fluctuation is subjected to terrestrial heat flux.

2.2 HYDROLOGY

The Karakoram and Himalayan mountains form the main source of snow and ice melt runoff to the Indus River System. The precipitation enhancing and shadowing effects of the main mountain ranges provide dramatic contrasts that greatly complicate the hydrological picture. Snowmelt predominates the south of the Himalayan crest. The Indus and its tributaries form the main drainage in the Karakoram-high Himalayan region. East to west, its main tributaries are Hunza, Shigar, Shyok, Astor, Gilgit, Ishkuman, Yasin, Ghizer, Yarkhun, Rich Gol, Arkari, Kunar, Panjkora, and Swat rivers.

2.2.1 RUNOFF

The Pakistan Water and Power Development Authority (WAPDA) have gauged the flow of the upper Indus since the early 1960s, at a string of flood monitoring stations upstream of Terbela. The gauging station on the Indus River at Partab Bridge just below the confluence of the Gilgit River covers the runoff of 142,700 km^2 catchment including the whole of the Karakoram mountains except for their NE slopes draining to the interior basins in western China. In 1976 WAPDA established gauging stations on the upper Indus at Kachura near Skardu south of the central Karakoram; on the Shyok River, which drains the eastern Karakoram; on the Hunza River at Dainyor Bridge near Gilgit in the western Karakoram; and on the Gilgit River just downstream of its confluence with the Hunza.

The Siachen is the first of a series of large glacier-fed tributaries of the Shyok River, which increase its annual runoff from 320 mm above the Siachen confluence of 5,000 km^2 to a mean of 910 mm during 1966-79 near Gilgit (catchment 13,200 km^2). The other gauged catchments in the Karakoram region have lesser percentages of permanent snow and ice cover and correspondingly lower annual runoff depths (Goudie et al., 1984). The monthly stream regimes throughout the Karakoram show very strong summer peaks attributing to glacier melt. Discharge decreases progressively throughout autumn and winter to a minimum in March, begins to rise with April snowmelt, but does not peak until July or August. A clear but considerably lagged diurnal cycle is interrupted by sharp recessions when snowfall or prolonged cloud cover halts glacier ablation. The general 20^{th} century movements of the Karakoram glaciers must also have affected runoff but no attempt has been made to quantify this. The river flow is affected by the creation of major natural dams as a consequence of either glacial, mudflow or landslide blocking (Goudie et al., 1984). Thereby the run off accumulation has resulted the recent flood outburst of Indus river which is a clear indication of global warming effects on glaciers volume, causing the historic catastrophe.

Salerno et al. (2008) studied variations in the surface area of glaciers in Sagarmatha National Park (Mount Everest region) for the second half of the 20th century. They found an overall decrease in glacier area by 4.9% (from 403.9 to 384.6 km^2) in four decades and they ascribed the decrease in area to a decrease in precipitation and hence a glacial retreat. They found that the glaciers oriented to the south show less decrease in area, in comparison with the glaciers oriented to other ordinal directions. The analysis in Manaslu area showed that Nepalese glaciers are retreating at the rate of 11 to 14 meters per year during the period of 1962 to 2008 (Salerno et al., 2008).

Fischer (2009) evaluated different methods of glacier volume calculations from ice-thickness data used on Austria glacier-Schaufelferner. The so calculated glacier volumes were compared with the ice-volume changes calculated from digital elevation models (DEMs) of the Austrian glacier inventories. The manually interpolated volumes based on the 1995 and 2003/06 ground penetrating radar (GPR) data yielded a volume loss of 0.021 km^3, only slightly different from volume loss of 0.020 km^3 calculated from the area / volume scaling algorithms applied to the Austrian glacier inventories data of 1997 and 2007. The calculation of volume change from surface elevation data seems to be more cost effective way of monitoring volume change, which is especially true on a timescale of decades (Fischer, 2009).

3 MATERIALS AND METHODS

The basic materials required for the compilation of volumetric estimation of glaciers are high quality topographic maps and temporal high resolution satellite data. The remote sensing data of land observation satellite Landsat-7 Thematic Mapper (TM) are used for the temporal analysis of glaciers and the identification of potentially dangerous depletion. A combination of digital satellite data and the Digital Elevation Model (DEM) of the area are used for better and more accurate results for the computation of volumetric calculations of glaciers.

Earth's ice cover is changing dramatically. Shrinking ice cover is a clear sign of global warming (Mare, 1997). Global ice melting accelerated during the 1990s, which was also the warmest decade on record. Ice is melting both at sea and on land, with shrinking mountain glaciers and thawing permafrost.

Ice is melting at a dramatic pace. Pakistan too is confronted with this problem. Three of the world's seven longest glaciers outside the Polar Regions are located in Pakistan (Figure 3.1) namely Siachen Glacier, Baltoro Glacier and Biafo Glacier which spread over an area of 72,496 km^2 and are reported to be melting fast.

This study work is restricted to Siachen glacier out of Shyok river basin and Baltoro and Biafo glaciers out of Shigar river basin of northern areas of Pakistan. The area is bounded by:-

- Shyok river basin 75^0 to 77^0 E Long and 34^0 to 35^0 N Lat
- Shigar river basin 75^0 to 77^0 E Long and 35^0 to 36^0 N Lat

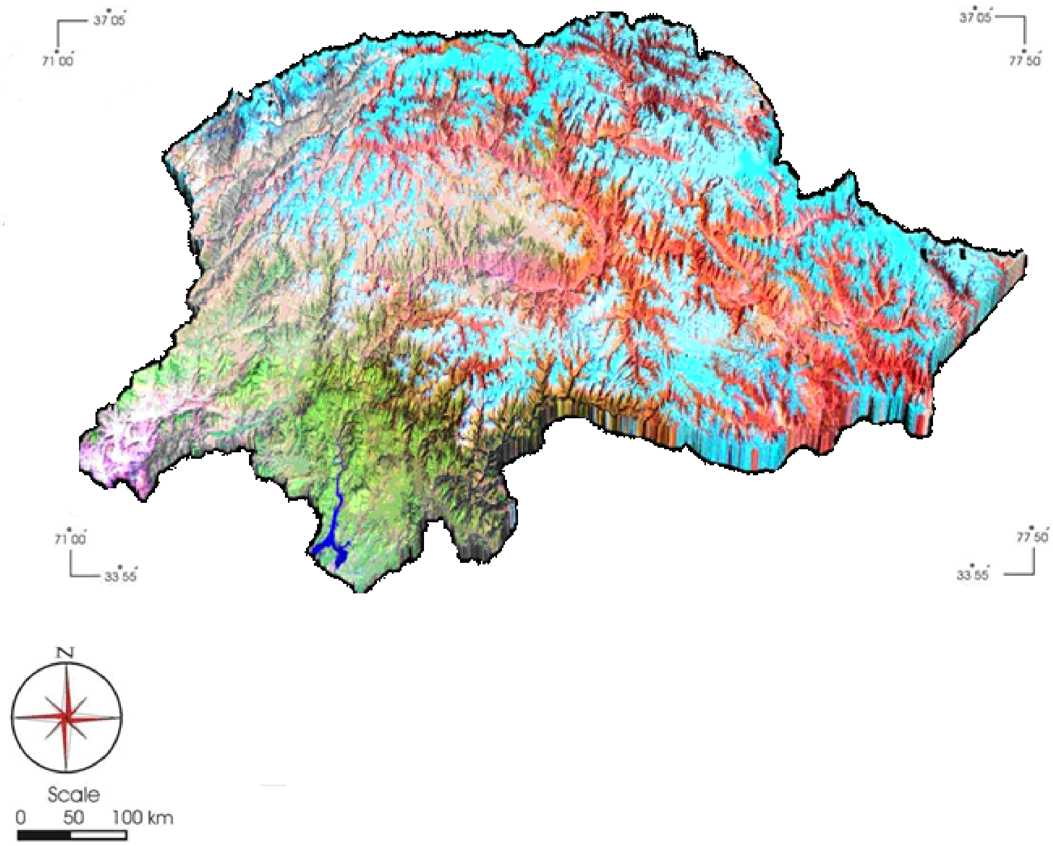

Figure 3.1: 3D views of glaciated areas of northern Pakistan generated with SRTM data of year 2000 of 90 m resolution.

3.1 DATA SETS

- Landsat-7 TM Images of Siachen, Baltoro and Biafo glaciers of northern Pakistan with a lag of 5/10 yrs in the decade of 1990-2000 obtained from SUPARCO (Appendix1).
- Digital elevation models of Baltoro, Biafo and Siachen glaciers from SRTM data of year 2000 and topographic maps of Svy of Pakistan of year 1990 (Appendix 2,3,4).
- Average annual temperature record of northern areas of Pakistan during the last decade obtained from Pakistan Meteorological department (Table 4.1 & 4.2).
- Satellite Radar Altimeter data for sea surface rise along coast line of Pakistan (Figure 4.6 & 4.7).

3.1.1 TOPOGRAPHIC MAPS

The glaciers are mostly concentrated in the north. The river basin boundary and spatial distribution of glaciers were identified from the satellite images and supplemented with the available topographic maps at scale of **1:250,000**. The topographic maps (43M, 52A and 52E) are the map series of the 1990 published by the Survey of Pakistan. These topographic maps are based on aerial photographs, field surveys at various times, and verification through large-scale topographic sheets.

3.1.2 SATELLITE IMAGE

The remote sensing data of Landsat-7 TM have been used for the spectral differentiation / delineating the boundry of the glaciers. The image data are in digital format and have a pixel size of 30m. Eleven scenes of Landsat-7 TM are required to cover the glaciated part of northern Pakistan (Figure 3.2).

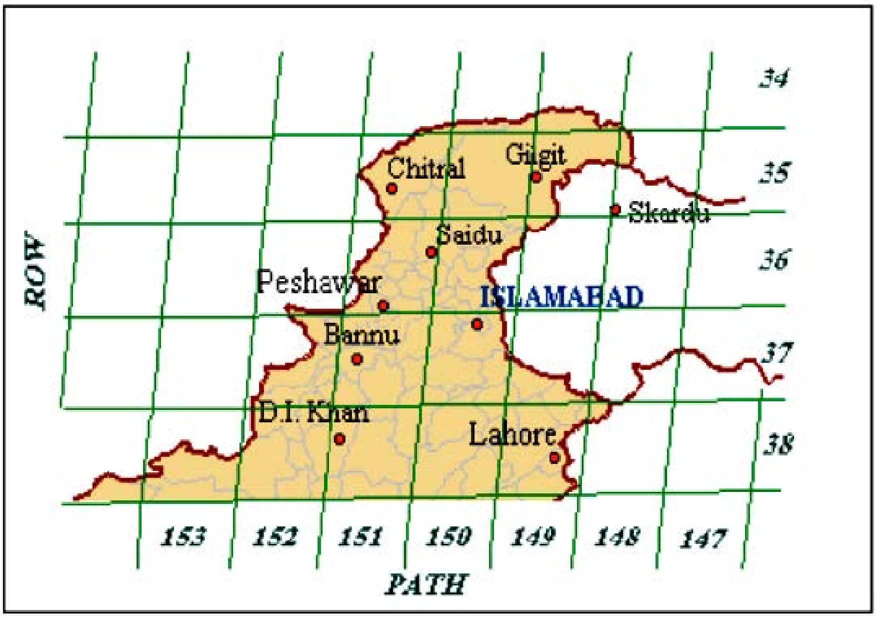

Figure 3.2: Scenes of Landsat-7 TM of northern Pakistan, datasets with lag of 5/10 years acquired from SUPARCO of 1990-2000.

For analysis of the Baltoro, Biafo and Siachen glaciers out of the two river basins Shyok and Shigar of northern areas, two scenes (147 and 148) of Landsat-7 of the period 1990 - 2000 were used.

3.1.3 SOFTWARE

- ERDAS IMAGINE
- ArcGIS
- Land serf
- Global Mapper

3.1.4 DIGITAL ELEVATION MODEL

Digital Elevation model (DEM) of study area having 30m resolution was generated from both the contours of topographic sheets of Survey of Pakistan and the SRTM data down loaded, thus obtaining the slope, aspect and elevation information.

3.2 MEAN GLACIER THICKNESS AND ICE RESERVE

All perennial snow and ice masses are observed for the study. Measurements of glacier dimensions are made with respect to carefully delineated drainage area for each ‘ice stream’. Tributaries are included in main streams when they are not seperable from one another. If no flow takes place between separate parts of a continuous ice mass, they are treated as separate units.

Delineation of visible ice, firn, and snow from rock and debris surfaces for an individual glacier does affect various study measurements. Marginal and terminal moraines are also included if they contain ice. The ‘inactive’ ice apron, which is frequently found above the head of the glacier, is regarded as part of the glacier. Perennial snow patches of large size are also included in the calculations. Rock glaciers are included if there is presence of large ice content.

The data based on different geophysical techniques available for the measurement of glacial ice thickness in the northern parts of Pakistan are available for only selected glaciers. To supplement the study results the mathematical model of ice thickness and ice reserves is incorporated. Measurements of glacial ice thickness in the Tianshan Mountains, China, show that the glacial thickness increases with the increase of its area (LIGG/WECS/NEA, 1988). The relationship between ice thickness (H in m) and glacial area (F in km^2) was obtained there as:

$$H = -11.32 + 53.21\, F^{0.3}$$

This formula has been used to estimate the mean ice thickness of the glaciers in meters. The ice reserves are estimated in km^3 by multiplying mean ice thickness by the glacial area. The area of the glacier is divided into accumulation area and ablation area (the area below the firn line). The volume of the glaciers is calculated using Digital Elevation Models of both times datasets by keeping the minimum elevation as threshold for plane height. The length of the glacier is divided into three columns: total length, length of ablation, and the mean length. The total (maximum) length refers to the longest distance of the glacier along the centerline. The mean value of maximum lengths of glacier tributaries (or firn basins) is the mean length.

The orientation of accumulation and ablation areas is represented in eight cardinal directions (N, NE, E, SE, S, SW, W, and NW). Some of the glaciers are capping just in the form of an apron on the peak, which is inert and sloping in all directions, and is represented as 'open'. The orientations of both the areas (accumulation and ablation) are the same for most of the glaciers.

Glacier elevation can be divided into highest elevation (the highest elevation of the crown of the glacier), mean elevation (the arithmetic mean value of the highest glacier elevation and the lowest glacier elevation), and lowest elevation. The glaciers identified and mapped in the satellite images are also mapped in the available topographic map and hence in this study the elevation of the glaciers is considered for both the datasets involving the contours of topographic sheets (1990) and point data of SRTM (2000).

3.3 IMAGE PROCESSING

The Land Sat-7 (TM) images are acquired from SUPARCO, georeferenced and then the desired Area of Interest (AOI) is extracted. Moreover the topographic maps were scanned and then after georefrencing, all were digitized to get GIS layers for analysis.

- The Landsat images are processed and georeferenced.
- Volume is calculated mathematically using height information extracted through DEMs.
- Decrease in glaciers volume is determined temporally with the lag of ten years.

3.4 METHODOLOGY

The study and acquisition of literature, topographic maps and satellite images for capturing the digital data of glaciers was carried out in first phase. Thereafter from maps and SRTM data the digital elevation models were generated for analysis of volumetric decrease of Siachen, Baltoro and Biafo glaciers. Finally the correlation with average temperature rise of northern areas and with sea level rise along coast line of Pakistan for computation of results was carried out. The methodology adopted in this study is shown in a flow chart (Figure 3.3).

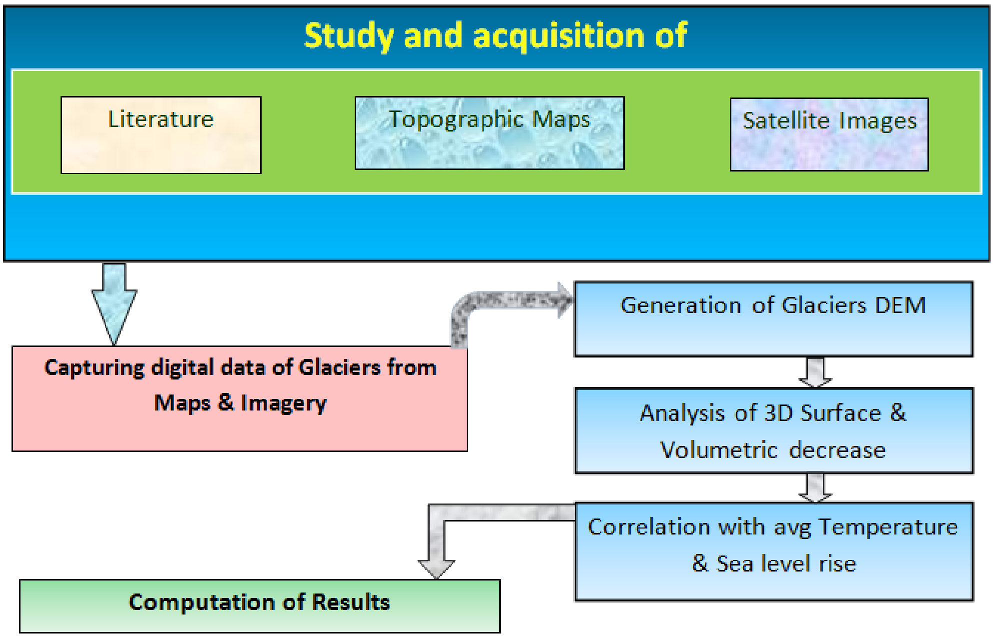

Figure 3.3: Methodological flow chart of capturing digital data of Siachen, Baltoro and Biafo glaciers for volumetric decrease estimates.

4 RESULTS AND DISCUSSION

The objectives of this study form the basis of all the analysis carried out in this chapter. The results are presented in the form of maps, charts, statistical tables and discussed appropriately. These include volumetric decrease of the three important glaciers of northern Pakistan during last decade, spatial distribution of the glaciated areas, correlation with average temperature rise in northern areas and correlation with sea surface rise along coastline of Pakistan.

The occurrence of glaciers has always been linked to climatic conditions. Climate is of fundamental importance to the inception and growth of glaciers. The form of the landscape dictates the threshold conditions for glacier occurrence and determines glacier morphology. Under certain climatic conditions for glaciation, glaciers of different shapes and sizes are formed depending on the landscape. Mountain glaciated regions are associated with climatic fronts and zones of maximum precipitation.

Alpine glaciers are generally situated at middle latitude regions of the globe. During most of the summer season, high flows in the Indus River system are due to snow and ice melt of alpine glaciers in the Himalayas. Hewitt (1990) states that evidences over the past 150 years indicate that the snow and ice cover of the upper Indus River basin undergoes large spatial as well as temporal variations.

The glacier area of northern Pakistan forms the single most concentrated source of runoff for the whole Indus basin. Since this frozen precipitation contributes more than 50% of the total flow of the Indus River System and a larger part of the future supplies upon which Pakistan can depend, knowledge of this resource seems a prime requirement for water resource and flood hazard monitoring on the Indus basin.

The glaciers in Karakoram region are high activity glaciers and have some of the steepest gradients in the world. According to their movement patterns, Karakoram and Himalayan glaciers are grouped into the following three categories:

- Glaciers with steady movement (these are also the longer ones)
- Glaciers having cyclic advances (these have short steep crevasses)
- Surging glaciers characterized by catastrophic advances

4.1 SHYOK RIVER BASIN

The Shyok River basin stretches over a latitudinal and longitudinal range of 34º 39' to 35º 42' and 75º 56' to 77º 27' respectively. This river basin is bounded with Jammu and Kashmir disputed Territory in south, China in northeast and Shigar and Indus River basins in the west. The elevation in the basin varies from more than 2,500 masl to more than 7,700 masl.

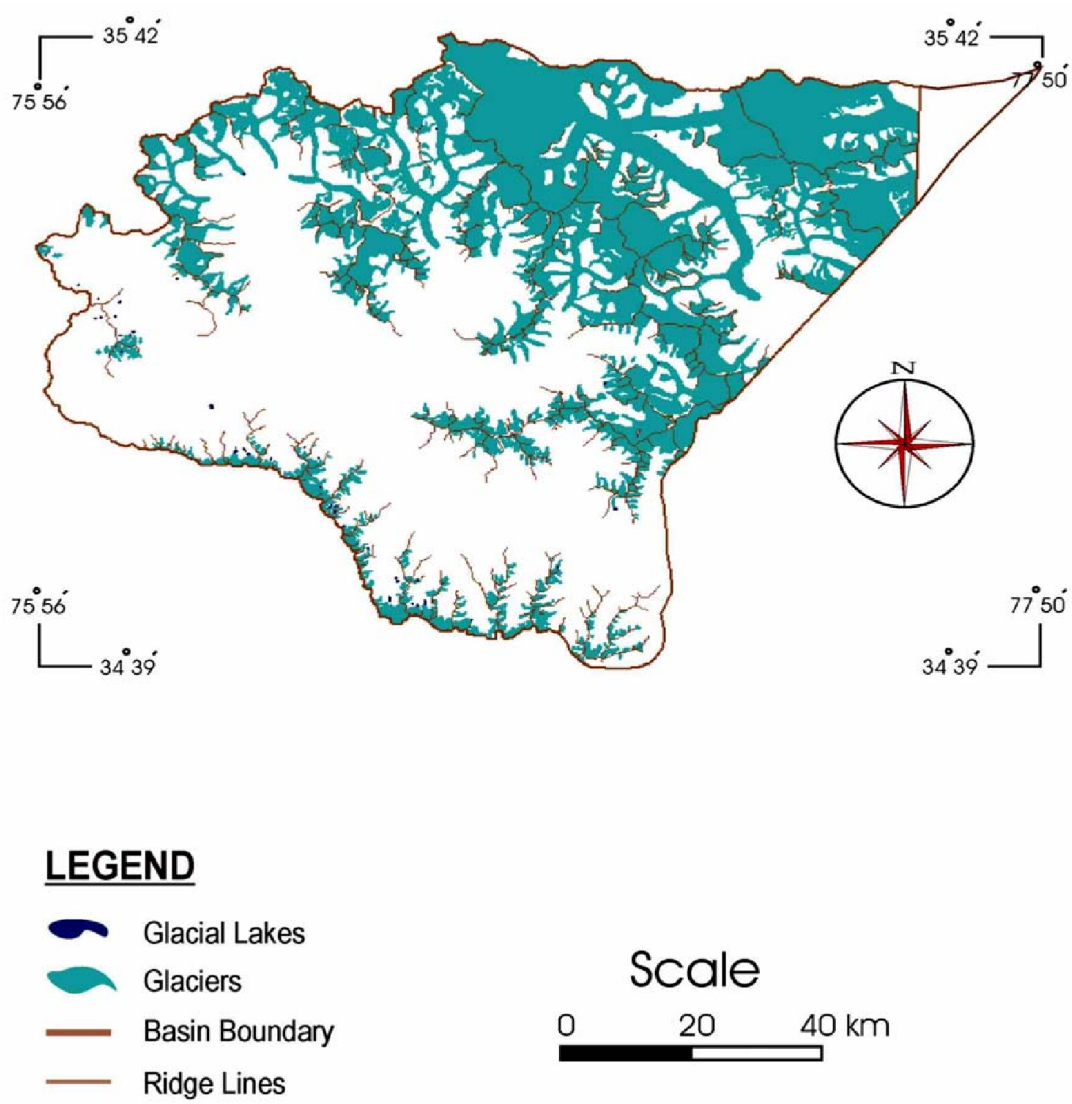

Figure 4.1: The glacier distribution in Shyok river basin showing Siachen glacier's significance in the region being the largest.

The total area of the basin is about 10,235 sq. km out of which 34.67% is under the glacier cover. There are 372 glaciers in the basin out of which 86% can be classified as mountain type glacier while only 14% are the Valley glaciers. The Siachen is the biggest valley glacier of this basin having an area of 1,112 sq. km. The Bilafond glacier is a large size Valley glacier having several supra glacial lakes.

4.1.1 SEASONAL SNOW COVERAGE OF SHYOK BASIN

The figure 4.2 shows that in the months of June, July and August are lowest that depicts high rate of melting during these months in this area. Whereas, comparison of the seasonal snow cover behavior of Shigar and Shyok basins shows that Shyok has high snow melting activities during the months of June, July and August.

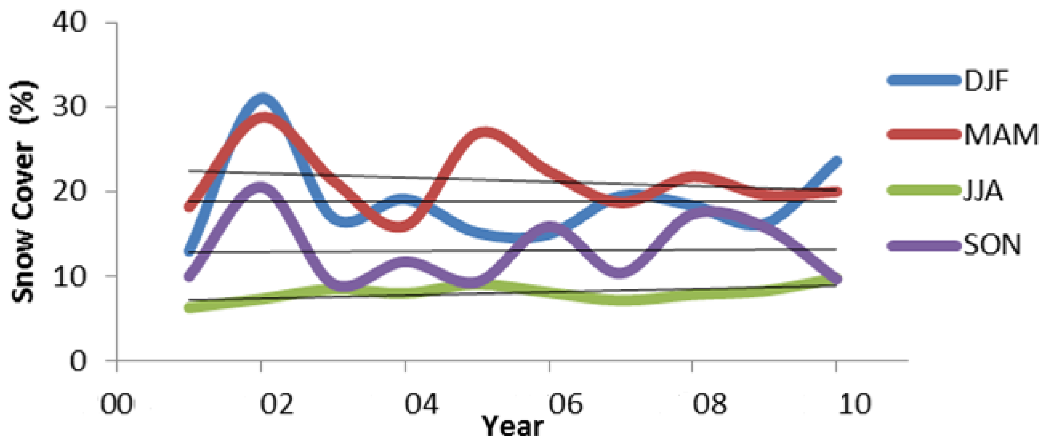

Figure 4.2: Snow Coverage of Shyok Basin in Km in a Decade

This result leads us to the conclusion that the anthropogenic activities in the region of Shyok are causing comparatively higher melting and thus more risks of glacial mass movement to occur. This may be verified by using high resolution satellite data and ancillary records.

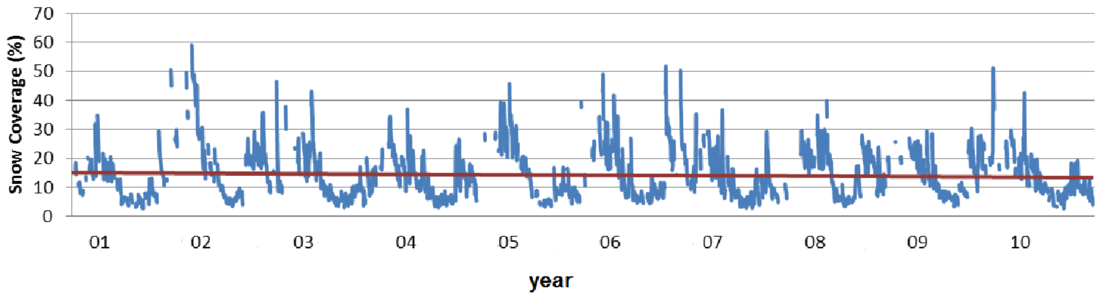

Figure 4.3: Temporal Assesment of Snow Coverage in a Decade in Shyok Basin

The snow cover trend is relatively stable in the Shigar area, whereas it is quite fluctuating in the Shyok. This fact again confirms high rate of changes over time being covered in the Shyok region which are cause melting and thus more chances of catastrophic events.

4.1.2 Aspect Wise Snow Coverage of Shyok Basin

The huge size glaciers are concentrated on NE and SE aspect of the basin. The SE and S aspects have the maximum glacier area of about 1,657 and 501 sq. km respectively owing to the fact that the larger glaciers like Siachen, Kondus, Bilafond, Ghandogoro, Masherbrum, etc. are facing to these aspects.

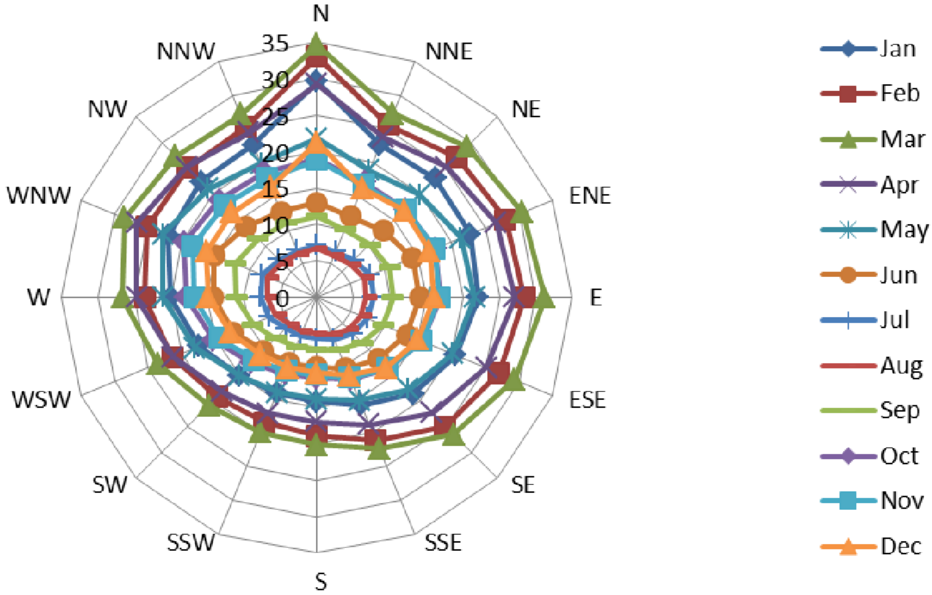

Figure 4.4: Aspect Wise Snow Coverage in Km in a Decade of Shyok Basin

The above figure shows aspects zone of N has maximum snow coverage whereas zones of W to ESE have minimum snow coverage over the year. Five different seasons and the aspect-wise snow distribution in these seasons can be seen easily from the figure. Here it is clear that the aspect zones N to NE and S to SW hold greater area of the basin than other aspect zones and the other aspect zones have maximum melting activities which may cause triggering of some catastrophic event in combination with factors such as seismic activity, high temperature and anthropogenic activity.

4.1.3 Distribution of Glaciers on Different Aspects in Shyok Basin

Table 4.1: Distribution of glaciers under different aspects in Shyok River basin

[redacted]											
Aspect	Number		Area (km2)				Length (m)			Ice Reserves (km3)	
	Total	%	Smallest	Largest	Total	%	Min.	Max.	Total	Total	%
N	48	12.9	0.23	13.65	111.63	3.15	390	5348	90014	7.802	0.87
NE	70	18.82	0.17	140.15	311.35	8.78	552	15085	154196	44.975	5.04
E	57	15.32	0.08	322.78	471.04	13.28	288	30587	152962	107.603	12.07
SE	48	12.9	0.21	1112.03	1656.52	6.69	540	76641	254334	576.934	64.69
S	57	15.32	0.18	177.69	500.74	14.11	533	21362	186446	87.127	9.77
SW	30	8.06	0.28	81.63	198.98	5.61	548	18219	109754	25.507	2.86
W	9	2.42	0.36	9.43	23.63	0.67	1135	5353	22387	1.658	0.19
NW	53	14.25	0.11	84.51	273.95	7.72	265	19948	123387	40.195	4.51
Total	372				3547.84				1093480	891.801	

4.2 SIACHEN GLACIER

The Siachen is the biggest valley glacier of this basin having an area of 1,056 sq. km followed by glacier having an area of more than 323 sq. km. The total length covered by the Valley glaciers is more than 500 km. The maximum length recorded for the Siachen glacier is 76.6 km. Since the inception of anthropogenic activities the Siachen glacier is showing abnormal behaviour. The Siachen glacier is subj to 2 km retreat during the last two decades which is the max retreat in the vicinity.

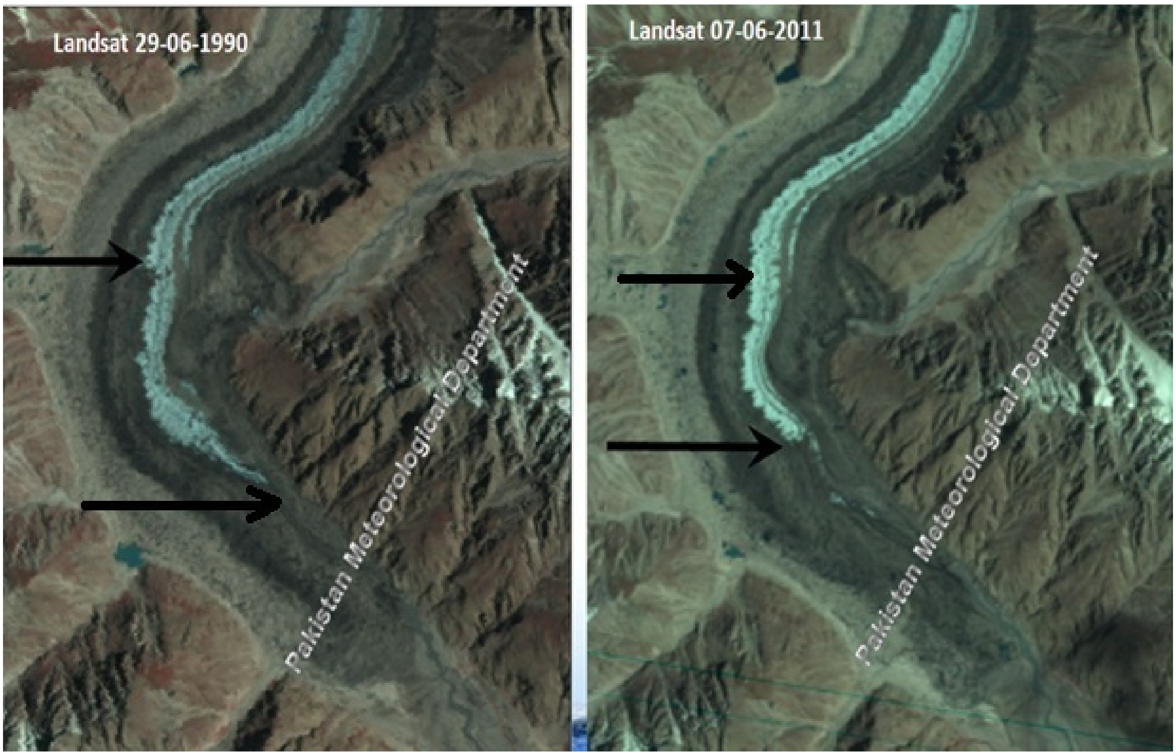

Figure 2.1: Siachen Glacier Retreat (2 km in 2 Decades)

After acquiring the image from SUPARCO, different band combinations were used for glaciers classification. Band ratio 4/5 gave the Siachen glacier's bounds (Appendix 4a). The resultant of Siachen glacier's shape file was ascertained after the identification of the bounds of the glacier (Appendix 4b). For volumetric decrease calculations the digital elevation models of both time bounds were generated (Appendix 4c). The contours of topographic map sheets of 1:25000 scale of Survey of Pakistan of 1990 were digitized for generation of DEM as one dataset (Appendix 4d). The SRTM data of 2000 was downloaded and there after the voids were removed with the help of land serf software and DEM of Baltoro glacier was generated for another dataset (Appendix 4e). Extract by mask utility was incorporated for computation of 3D surface area and volume of glacier having established the plane height (Appendix 4f).

The volumetric decrease of Siachen glacier subjected to global warming during the last decade is computed as following:

Siachen-93

- Plane height: 3300 m
- 3D area: 1056×10^6 m^2
- Volume: 1631×10^9 m^3

Siachen-98

- Plane height: 3300 m
- 3D area: 1043×10^6 m^2
- Volume: 1541×10^9 m^3

Volumetric decrease over 5 years = 90×10^9 m^3, i.e., 5.55 %

Volumetric decrease over 10 years = 11.10 %

The mathematical model of mean glacier thickness and ice reserves has a relationship:-

$$\mathbf{H = -11.32+53.21\ F^{0.3}}$$

Where, H = Ice thickness in meters

F = Glacial area in km^2

This model gives the following results in the volumetric decrease:-

Siachen-93

- Glacial area: $1056 \times 10^6\ m^2$
- Thickness: 419 m
- Ice reserve: 441 km^3

Siachen-98

- Glacial area: $1043 \times 10^6\ m^2$
- Thickness: 416 m
- Ice reserve: 421 km^3

Decrease in ice reserves over 5 years = 20 km^3, i.e., 4.8 %

Decrease in ice reserves over 10 years = 9.6 %

4.3 SHIGAR RIVER BASIN

The Shigar River basin is situated in the latitude and longitude range of 35º 19' to 36º 07' N and 74º 53' to 76º 45' E respectively (Figure 4.2). The elevation range varies from about 2,500 m to more than 8,600 m.

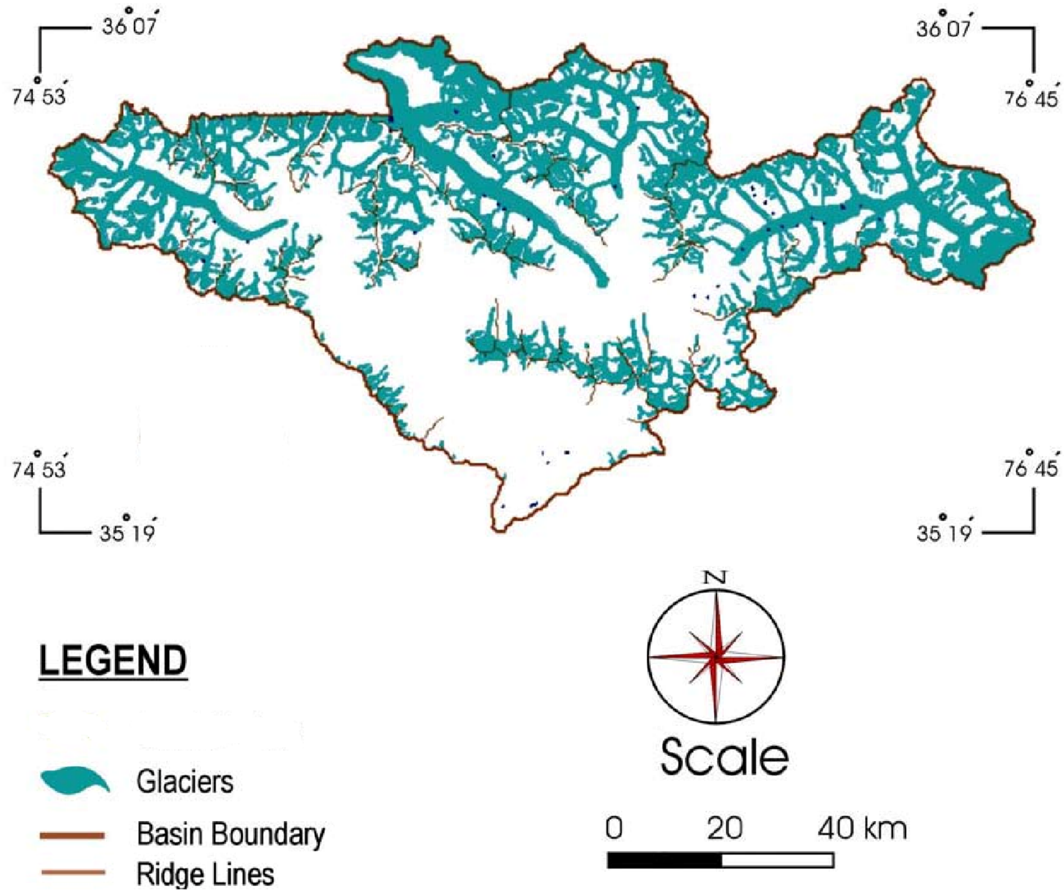

Figure 4.2: The glacier distribution in the Shigar river basin showing Baltoro and Biafo glaciers significance in the region being the largest.

The basin stretches over an area of 7,382 km^2 out of which, the glacier area is about 2,240 km^2. The distribution of different types of the glaciers is presented in Figure (4.2). The large size glaciers are mainly concentrated on the N, NE and NW aspects. The total ice reserves of this basin are 581 km^3.

4.3.1 SEASONAL SNOW COVERAGE OF SHIGAR BASIN

The figure 4.3 shows that the months of June, July and August are lowest that depicts high rate of melting during these months in this area. Whereas, comparison of the seasonal snow cover behavior of Shigar and Shyok basins shows that Shyok has high snow melting activities during the months of June, July and August.

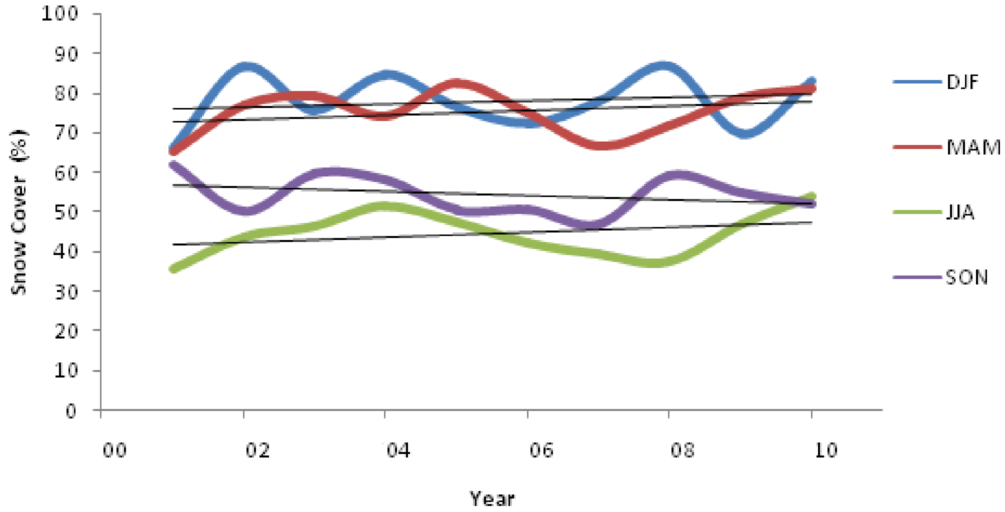

Figure 4.3: Snow Coverage of Shigar Basin in Km in a Decade

This result leads us to the conclusion that the anthropogenic activities in the region of Shyok are causing comparatively higher melting and thus more risks of Gayari like incident to occur. This may be verified by using high resolution satellite data and ancillary records.

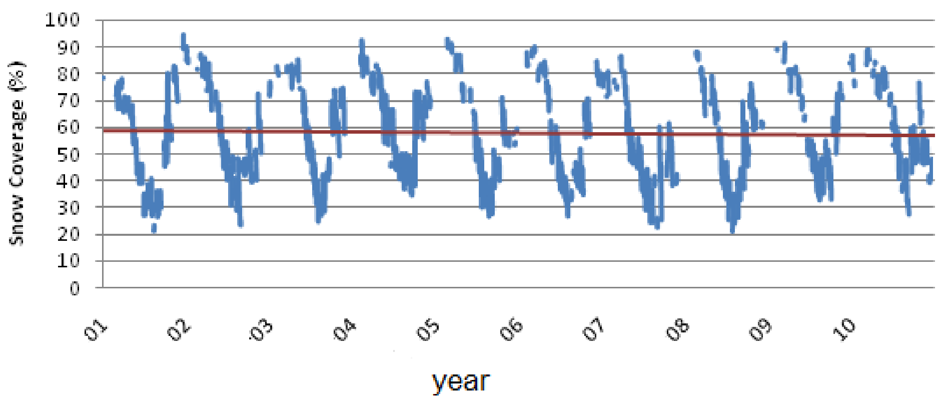

Figure 4.4: Temporal Assesment of Snow Coverage in Shigar in a Decade

The snow cover trend is relatively stable in the Shigar area, whereas it is quite fluctuating in the Shyok. This fact again confirms high rate of changes over time being covered in the Shyok region which are cause melting and thus more chances of catastrophic events.

4.3.2 ASPECT WISE SNOW COVERAGE OF SHIGAR BASIN

The huge size glaciers are concentrated on SW and SE aspect of the basin. The SE and W aspects have the maximum glacier area of about 1,111 and 693 sq. km respectively owing to the fact that the larger glaciers like Biafo and Baltoro etc. are facing to these aspects. The two out of world's seven largest glaciers lie in Shigar river basin. The Baltoro glacier with a length of 59 km has the maximum area of 633 km^2 and the Biafo glacier has maximum length of 62.6 km covering an area of 404 km^2.

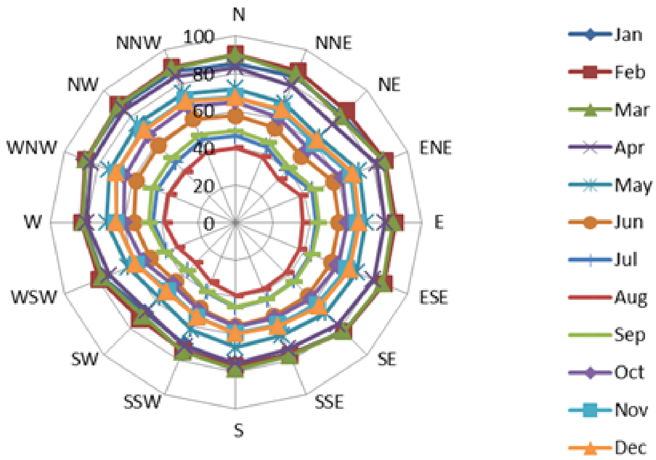

Figure 4.5: Aspect Wise Snow Coverage in Km of Shigar Basin

The figure 4.5 shows aspects zone of N has maximum snow coverage whereas zones of W to ESE have minimum snow coverage over the year. Five different seasons and the aspect-wise snow distribution in these seasons can be seen easily from the fig 4.22. Here it is clear that the aspect zones N to NE and S to SW hold greater area of the basin than other aspect zones and the other aspect zones have maximum melting activities which may cause triggering of some catastrophic event in combination with factors such as seismic activity, high temperature and anthropogenic activity.

4.3.3 Distribution of Glaciers on Different Aspects in Shigar River Basin

Table 4.8: Distribution of glaciers under different aspects in Shigar Basin

Aspect	Number		Area (km2)				Length (m)			Ice Reserves (km3)	
	Total	%	Smallest	Largest	Total	%	Min.	Max.	Total	Total	%
N	26	13.40	0.08	27.74	97.64	4.36	290	13123	89716	9.98	1.72
NE	38	19.59	0.09	11.19	79.97	3.57	469	8559	113071	5.81	1.00
E	27	13.92	0.06	10.47	36.70	1.64	250	6460	51590	2.42	0.42
SE	32	16.49	0.11	426.09	1111.14	49.60	344	62624	230256	304.69	52.42
S	17	8.76	0.26	53.27	124.54	5.56	724	15324	74293	16.67	2.87
SW	17	8.76	0.23	7.40	41.60	1.86	392	6675	60337	2.85	0.49
W	16	8.25	0.08	641.21	693.86	30.97	355	58970	107300	234.79	40.39
NW	21	10.82	0.13	11.97	54.63	2.44	604	8233	66950	4.07	0.70
Total	194				2240.08				793513	581.27	

The two out of world's seven largest glaciers lie in Shigar river basin. The Baltoro glacier with a length of 59 km has the maximum area of 633 km^2 and the Biafo glacier has maximum length of 62.6 km covering an area of 404 km^2.

4.4 BALTORO GLACIER

After acquiring the image from SUPARCO, different band combinations were used for glaciers classification. Finally with band ratio 4/5 and the thermal band Baltoro glacier's bounds were identified (Appendix 2a). The resultant of Baltoro glacier's shape file was ascertained after the identification of the bounds of the glacier (Appendix 2b). For volumetric decrease calculations the digital elevation models of both time bounds were generated (Appendix 2c). The contours of topographic map sheets of 1:25000 scale of Survey of Pakistan of 1990 were digitized for generation of DEM as one dataset (Appendix

2d). The SRTM data of 2000 was downloaded and there after the voids were removed with the help of land serf software and DEM of Baltoro glacier was generated for another dataset (Appendix 2e). Extract by mask utility was incorporated for computation of 3D surface area and volume of glacier having established the plane height (Appendix 2f).

The volumetric decrease of Baltoro glacier is computed having established the parameters for both the datasets, as shown below:

Baltoro-90

- Plane height: 3420 m
- 3D area: 633 X 10^6 m^2
- Volume: 1031 x 10^9 m^3

Baltoro-98

- Plane height: 3420 m
- 3D area: 609 X 10^6 m^2
- Volume: 978 x 10^9 m^3

Volumetric decrease = 53 x 10^9 m^3, i.e., 5.14 %

The mathematical model of mean glacier thickness and ice reserves has a relationship: $H = -11.32+53.21\ F^{0.3}$, here H = Ice thickness in meters, F = Glacial area in km^2. This model gives the following results in the volumetric decrease:

Baltoro-90

- Glacial area: 633 x 10^6 m^2
- Thickness: 357 m
- Ice reserve: 226 km^3

Baltoro-98

- Glacial area: 609 x 10^6 m^2
- Thickness: 353 m
- Ice reserve: 214 km^3

Decrease in ice reserves = 12 km^3, i.e., 5.30 %

4.5 BIAFO GLACIER

Biafo glacier's bounds were identified (Appendix 3a) using ratio of band 4 to band 5. The resultant of Biafo glacier's shape file was ascertained after the identification of the bounds of the glacier (Appendix 3b). For volumetric decrease calculations the digital elevation models of both time bounds were generated (Appendix 3c). The contours of topographic map sheets of 1:25000 scale of Survey of Pakistan of 1990 were digitized for generation of DEM as one dataset (Appendix 3d).

The SRTM data of 2000 was downloaded and there after the voids were removed with the help of land serf software and DEM of Biafo glacier was generated for another dataset (Appendix 3e). Extract by mask utility was incorporated for computation of 3D surface area and volume of glacier having established the plane height (Appendix 3f).

The volumetric decrease of Biafo glacier is computed having established the parameters for both the datasets, and shown below:

Biafo-93

- Plane height: 3060 m
- 3D area: 404 X 10^6 m^2
- Volume: 686 x 10^9 m^3

Biafo-98

- Plane height: 3060 m
- 3D area: 398 X 10^6 m^2
- Volume: 673 x 10^9 m^3

Volumetric decrease =13 x 10^9 m^3, i.e., 1.90 %

Using the mathematical model, the ice reserves in Biafo glacier are estimated as under:

Biafo-93

- Glacial area: 404×10^6 m^2
- Thickness: 311 m
- Ice reserve: 126 km^3

Biafo-98

- Glacial area: 398×10^6 m^2
- Thickness: 309 m
- Ice reserve: 123 km^3

Decrease in ice reserves = 3 km^3, i.e., 2.18 %

The volumes of ice estimated at two different times were compared to one another to estimate the volume loss (Table 4.1). The volumes calculated here are actually the volumes of the ice and the underlying rock to the depth of plane height (the height of terminus of the glacier; Figure 4.3). The thickness of this ice-plus-rock column is the difference of elevation between terminus and the point where from the glacier originates. Using these volumetric comparisons, Baltoro glacier's volumetric loss over 8 years is estimated to be 5.14 %, where as in Biafo and Siachen glaciers the volumetric loss over 5 years is estimated as 1.90 and 5.55 %, respectively. The calculated estimates of percentage decrease of ice volume over 5 years (Biafo and Siachen glaciers) and over 8 years (Baltoro glacier) were recalculated to represent volume loss over a decade (10 years). The recalculated percentage decrease of ice volumes are Baltoro 6.43%, Biafo 3.79%, and Siachen 11.09%.

SUMMARY OF VOLUME ESTIMATES

Table 4.1: Summary of volume computations of Baltoro, Biafo and Siachen glaciers during the period from 1990-1998 using areal bounds from remote sensing data and using mathematical model.

	Study Volumetric Decrease			Mathematical Model	
	Plane Height (m)	3D Area (km^2)	Volume (km^3)	Ice Thickness (m)	Ice Reserve (km^3)
Baltoro-90	3420	633	1031	357	226
Baltoro-98	3420	609	978	353	214
Biafo-93	3060	404	686	311	126
Biafo-98	3060	398	673	309	123
Siachen-93	3300	1056	1631	419	441
Siachen-98	3300	1043	1541	416	421

The difference in glaciers percentage volumetric decrease is because of the aspect, slope, geothermal gradient, density and glacier bed rock topography. The following assumptions are made in ice volume calculations (Figure 4.3):

- The plane height is the elevation of the terminus of the glacier.
- The highest elevation is where a glacier originates.
- The thickness used in volume calculations of ice and the underlying rock is the difference of elevation between the plane height and the highest elevation.
- Since the exact ice thickness above the rock across the length of the glacier can not be determined without drilling or geophysical equipment, it is assumed that a uniform layer of ice exists in the glacier from head (where glacier originates) to toe (glacier terminus).
- The density of the glacier and the rock combination is same and constant throughout the length and thickness of the glacier.
- There is no rock or glacier debris around to modify the volume calculations.
- Crevasses in the glacier are not large enough to modify the volume calculations.
- A schematic cross-sectional profile (Figure 4.3) of glaciated area is presented to show the actual volume calculated versus the existence of ice and underlying rocks.

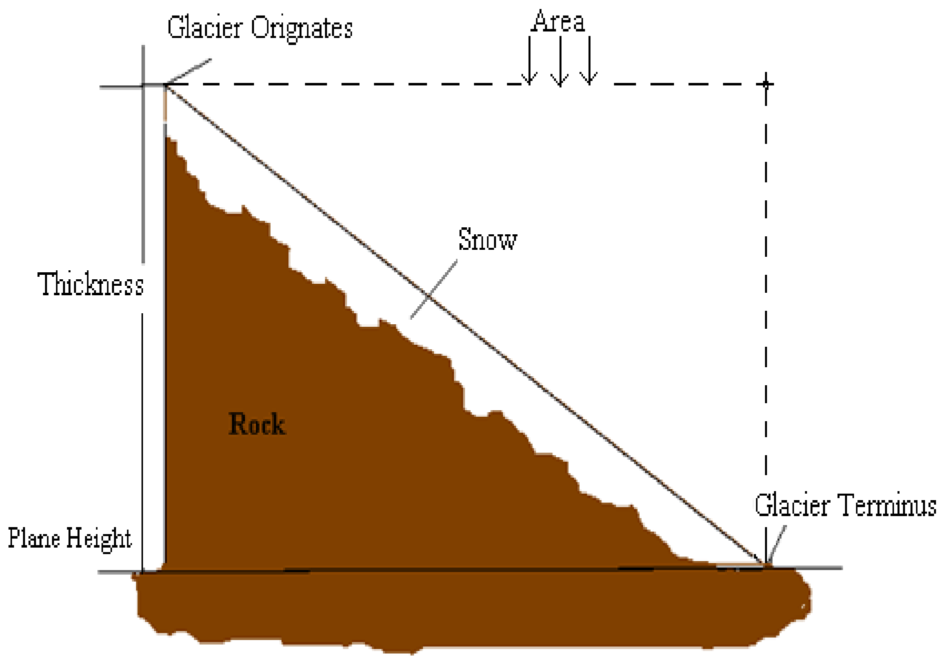

Figure 4.3: A schematic cross-sectional profile of glaciated area showing input parameters in volume calculations and comparison for volume loss over time.

4.6 GLOBAL TEMPERATURE RISE

Greenhouse gases in our atmosphere have increased since 1750 due to the consumption of fossil fuels**,** new forms of land use, and agriculture. The massive increase in greenhouse gases has lead to a rise of average temperatures by 0.74 ^{0}C since 1900. The last half of the 20th century has been the hottest period in the Northern Hemisphere (IPCC, 2007). The average temperature rise in northern areas of Pakistan in the last decade is 1.78 ^{o}C which is correlated with volumetric decrease of Siachen, Baltoro and Biafo glaciers.

To a great extent, weather patterns are predicted to change in response to global warming. Mean yearly temperature of northern areas based on five meteorological stations dataset of 1990 is 20.64 ^{o}C (Table 4.2; PMD, 1990) and that of 2000 is 22.42 ^{o}C (Table 4.3; PMD, 2000).

Table 4.2: Mean monthly temperature in 1990 in northern areas of Pakistan, dataset of selected stations provided by PMD for the correlation of average temperature rise with volumetric decrease of glaciers.

Month	Skardu	Bunji	Gilgit	Astore	Chilas
Jan-90	1.2	9.3	8.6	2.6	10.5
Feb-90	2.1	8.6	9.3	5.5	10.6
Mar-90	8.4	17.5	17.3	7.5	17.5
Apr-90	16.6	24.4	24.9	14.5	27.3
May-90	27.0	32.6	34	24.5	36.3
Jun-90	26.8	31.8	32.2	24.1	35.8
Jul-90	27.3	30.9	30.6	22.4	35.1
Aug-90	27.8	32.7	32.5	23.5	37.2
Sep-90	26.7	30.8	30.1	23.3	36.5
Oct-90	19.5	26.3	27.2	18.8	26.7
Nov-90	12.3	18.9	19	11.2	19.5
Dec-90	2.3	11.5	11.2	4.1	13.2
Yearly Average	16.5	22.94	23.07	15.16	25.52

The change of mean annual temperature from 20.64 ^{o}C in 1990 to 22.42 ^{o}C in 2000 (1.78 ^{o}C change over 10 years period) probably has caused directly or indirectly, the change in the precipitation regime and hence glacial retreat. Therefore the mean monthly temperature of Skardu, Bunji, Gilgit, Astore and Chilas is considered for this change detection, which is causing melting of alpine glaciers of northern areas.

Table 4.3: Mean monthly temperature in 2000 in northern areas of Pakistan, dataset of selected stations provided by PMD for the correlation of average temperature rise with volumetric decrease of glaciers.

Month	Skardu	Bunji	Gilgit	Astore	Chilas
Jan-00	1.8	10.9	10.6	3.6	12.7
Feb-00	3.4	12.6	13.3	2.9	14.6
Mar-00	11.9	19.1	19.3	9.5	20.5
Apr-00	20.1	25.9	26.5	17.5	28
May00	27.5	33.7	34.9	24.9	37.3
Jun-00	29.3	34.3	35.2	25.3	37.8
Jul-00	30.3	34.9	34.6	26.4	38.1
Aug-00	29.6	34.8	35.3	25.5	38.2
Sep-00	26.9	31.8	32.9	23.9	35
Oct-00	21	26.6	27.8	19.8	29.7
Nov-00	13.3	19.4	19.9	12.1	21.5
Dec-00	4.5	13.1	12.9	5.7	14.9
Yearly Average	18.3	24.75	25.26	16.43	27.36

4.7 RISING SEA SURFACE

One of the most often stated pieces of drivel from the climate science community, is that sea level rise is an indication of warming temperatures. In fact, majority of the glaciers all over the world are apparently declining, which is considered as an effect and result of temperature rise among other factors and components of climate change. IPCC (2007) reveal that sea levels have risen almost 17 centimeters during the 20th century. Probably the sea level is rising due to a collective impact of more and more water being released from glacial retreat due to global warming and of volume increase of water due to temperature rise. The sea surface rise along coast line of Pakistan is determined from satellite radar altimeter data (Figure. 4.4). Sea level rise is nearly 14mm within the last decade (IPCC, 2007).

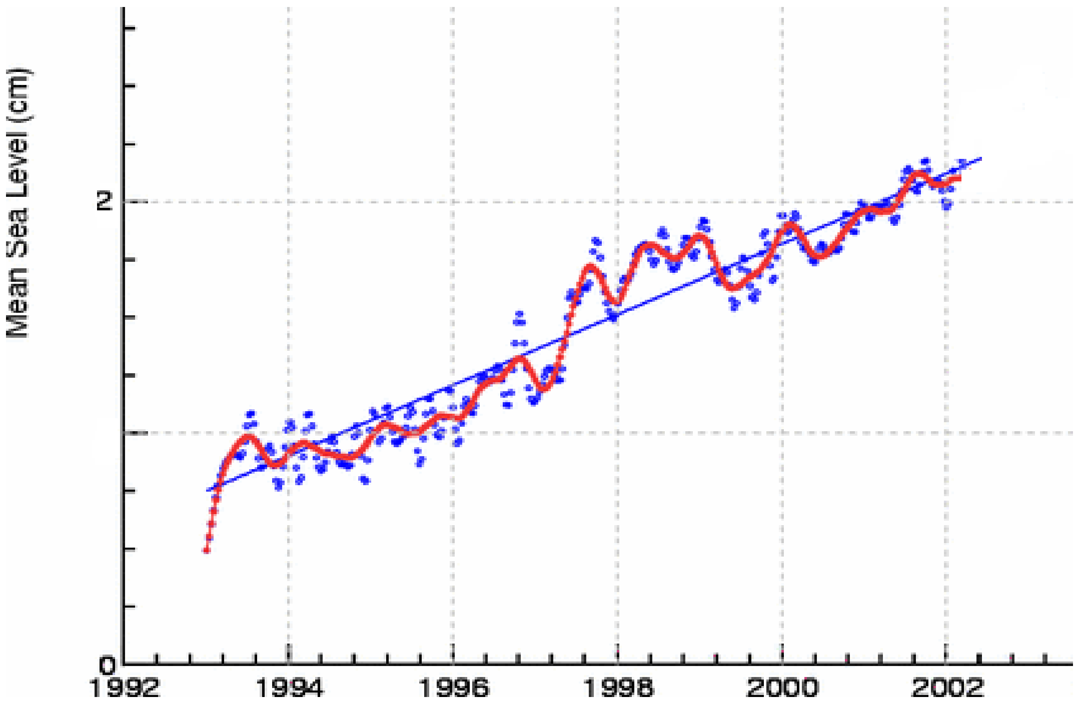

Figure 4.4: Estimated altimetry mean sea level along coastline of Pakistan (Oct 1992 – Sep 2002; IPCC, 2007).

The trend of mean sea level for Pakistan Harbor is taken from the sea level trends (Oct 1992 – Sep 2002) of the world (IPCC, 2007) shown in Figure 4.5. The increasing pattern in sea level trend has been taken as a base reference to ascertain the range of sea level rise along Pakistan coast. The estimated sea level trends show that the sea level rise along the coastline of Pakistan is within 10 to 15 mm range (Oct 1992 – Sep 2002: Figure. 4.5).

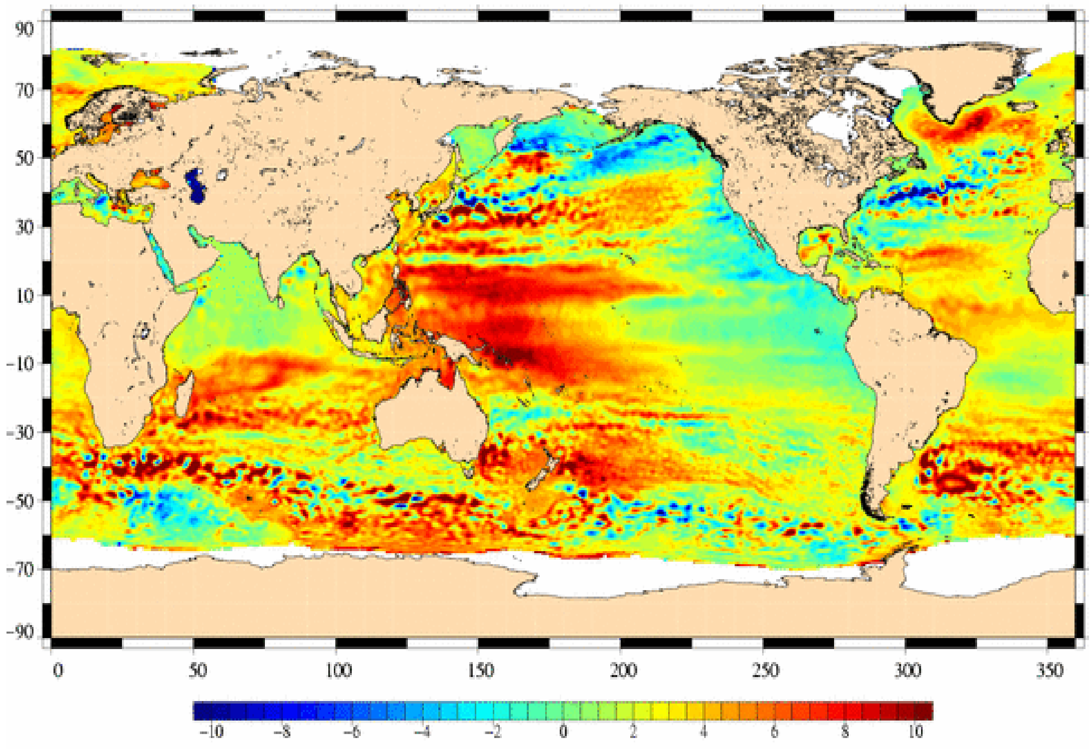

Figure 4.5: Estimated sea level trends of the world showing sea level along coastline of Pakistan within 10 to 15 mm range (Oct 1992 – Sep 2002; IPCC, 2007)

4.8 RELATIONSHIP

Glaciers are formed under conditions of sub-zero temperatures and abundant snow precipitation. Warmer temperatures and possibly reduced snow precipitation are responsible for their melting and retreating. Melting of Alpine glaciers has been particularly striking since the 1980's. Alpine glaciers had already lost more than 25% of their volume in the 50 years before the exceptionally hot and dry summer 2000 and roughly one third of their original volume since 1850 (Bundesministrium, 2003). Glaciers will experience a substantial retreat during the 21st century and the duration of snow cover is expected to decrease substantially for each °C of temperature increase at mid elevations (Bundesministrium, 2003). Glaciers will suffer a further volume reduction. Glacier retreat is expected to enhance summer flow of the alpine rivers. As they retreat, glaciers leave important masses of unstable rock material, which may contribute to debris flows.

The estimated total glacier volume loss in the alpines during the last decade corresponds to 5-10% of the remaining ice volume. As with 1.78 ^{o}C temperature rise, the average volumetric decease of Siachen, Baltoro and Biafo glaciers during the last decade is 7 % and the sea level rise along coast line of Pakistan is 14 mm, the resultant relationship applying unit rule is, “with temperature rise of 1^{o}C in northern areas of Pakistan, the volumetric decrease of alpine glaciers of Pakistan would be 4 % and sea level rise would be 8 mm along coast line of Pakistan”.

5 CONCLUSION & RECOMMENDATIONS

The study of three important glaciers of northern areas of the Pakistan and their volume estimation is carried out. The study area comprised two river basins, the Shyok and Shigar. Using remote sensing data and the topographic maps available at a scale of 1:250,000 the study was completed. For volumetric decrease of glaciers, the methodology adopted is followed to achieve the subject results.

5.1 CONCLUSION

Glaciers are major sources of water, studying the volumetric decrease with temporal analysis is vital for planning, development water resource conservation, flood monitoring and mitigation activities. The major sub basins of Indus River in HKH region of Pakistan are Shyok and Shigar. Most of the snow and ice reserves are concentrated in the mountain ranges lying in these basins. These river basins contain the glaciated part in northern Pakistan, which forms the headwaters of the main Indus basin.

In this report the information given is about volumetric decrease of the three largest glaciers, Siachen, Baltoro and Biafo of HKH region of the country. In northern areas the total glaciated area is about 15,041 km^2 which is 11.7% of the total area. The volumetric decrease of these glaciers is calculated as 4 % with an increase of 1^{0}C average temperature rise during the last decade. The total ice reserve estimated in these basins is about 2,738 km^3. Altogether, more than 80% of the ice reserves are contributed collectively by Shyok (32%), Shyok (30%) and Shigar (21%) river basins. The ice reserves are subjected to manifest of global warming which is causing their decay. Overall in these basins, maximum glaciers are oriented towards north and northeast. The aspect is one of the major factors for volumetric decrease of the glaciers. Each basin behaves differently owing to the orientation of the glaciers in various ordinal directions.

There are several impacts of glaciers volumetric decrease which need monitoring and early warning systems. The most important mitigation measure for reducing the risk is to reduce the volume of water in the glacial pockets in order to reduce the peak surge discharge. Downstream in flood prone areas, measures should be taken to protect infrastructure against the destructive forces of outburst floods, as a resultant of volume decay of glaciers. Careful evaluation by detailed studies of the lake, mother glaciers, damming materials, and the surrounding conditions are essential in choosing an appropriate mitigation measure. Controlled breaching can be carried out by blasting, excavation, or even by dropping bombs from an aircraft to avoid possible peak surge discharge from glacial pockets. The volumetric decrease of these glaciers is probably due to global warming, which is a consequence of a host of factors, such as increase in greenhouse gases and decrease in ozone layer. An immediate result of melting glaciers is a rise in sea levels. Even a modest rise in sea levels could cause flooding problems for low-lying coastal areas like Karachi. Antecedent global warming factors need to be monitored and mitigated to safe guard the alpine glaciers.

5.2 RECOMMENDATIONS

The integration of visual and digital image analysis with GIS provided useful utilization for the study of glaciers. For further study and studies following propositions are made:

- Fine resolution data be acquired, to more accurately define the boundary of glaciers.
- Mathematical / empirical models be developed for ice volume calculations and for manipulations of RS data.
- Geophysical data on depth of glaciers / thickness of glaciers be collected through Pakistan Army units posted in the glaciated areas.
- The dangerous moraine dams, especially near the headwaters and settlements, needs to be monitored regularly, which are there as a consequence of volumetric decrease of these glaciers.
- In the HKH region, many rivers flow down from the high Himalayan or Tibetan Plateau to more than one country. Flash floods from landslide dam failure or glacial outburst in one country can cause havoc in the downstream areas of other countries. So inter-country flood warning systems should be established in the river valleys. A mechanism for sharing the costs and benefits of flash flooding mitigation works should be devised.

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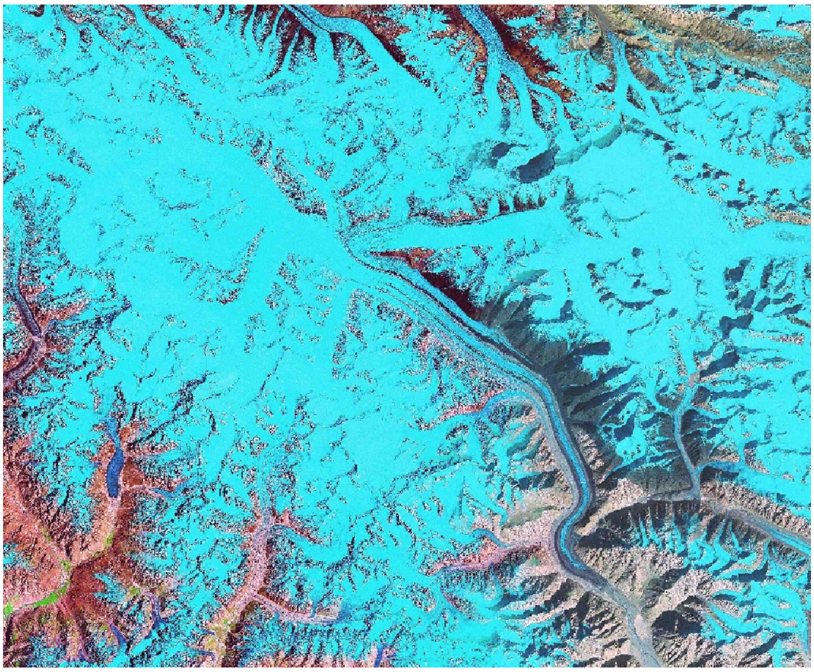
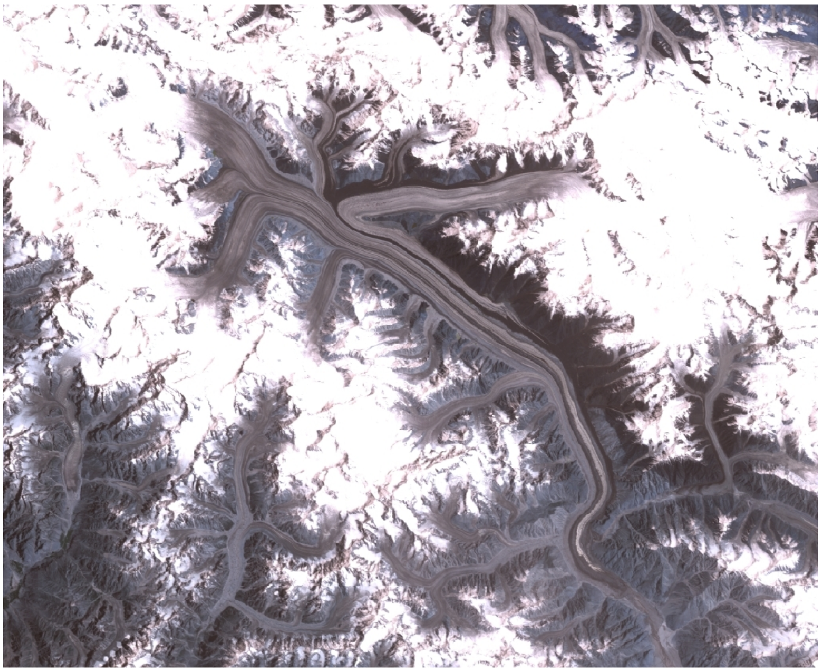
APPENDICES

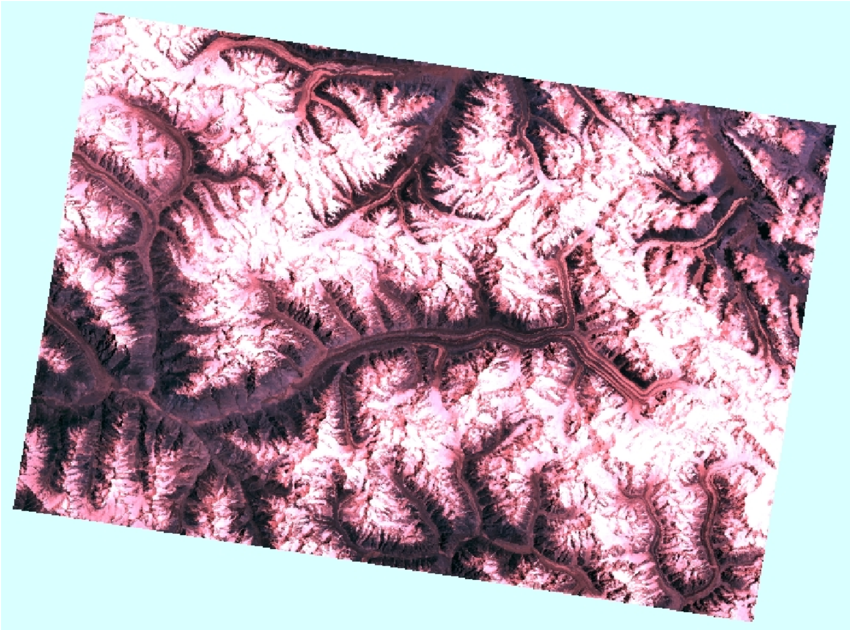
APPENDIX 1(A): SCENE OF LANDSAT-7 TM OF SIACHEN GLACIER (1993)



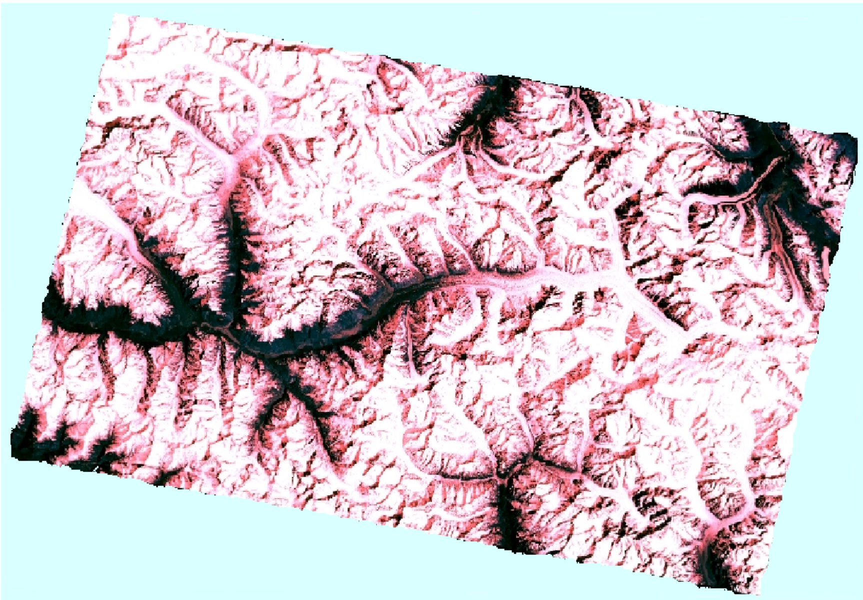
APPENDIX 1(B): SCENE OF LANDSAT-7 TM OF SIACHEN GLACIER (1998)



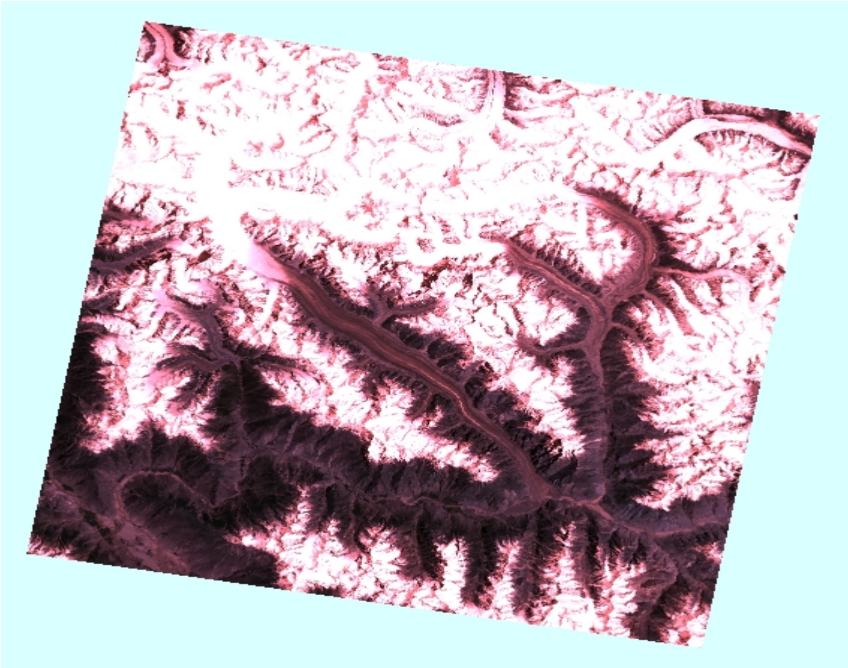
APPENDIX 1(C): SCENE OF LANDSAT-7 TM OF BALTORO GLACIER (1990)



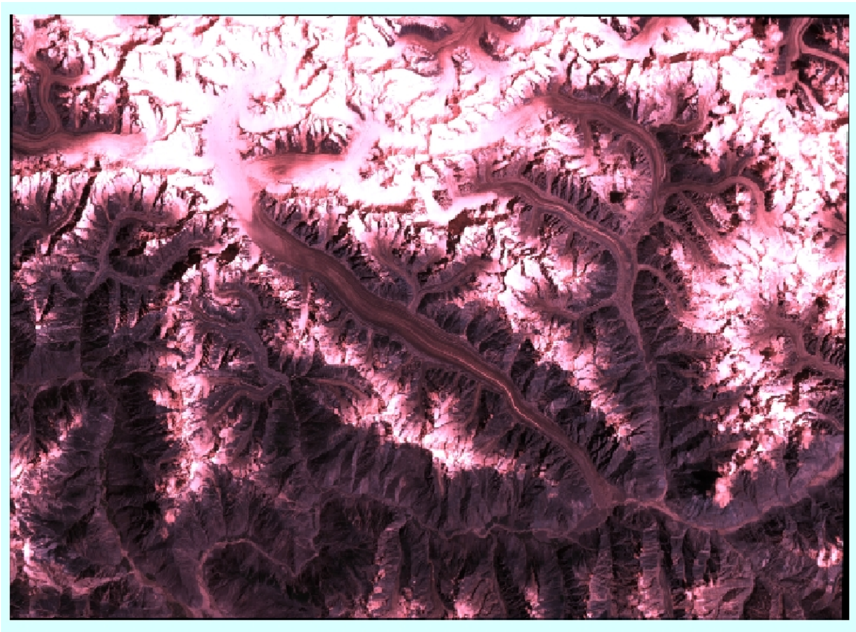
APPENDIX 1(D): SCENE OF LANDSAT-7 TM OF BALTORO GLACIER (1998)



APPENDIX 1(E): SCENE OF LANDSAT-7 TM OF BIAFO GLACIER (1993)



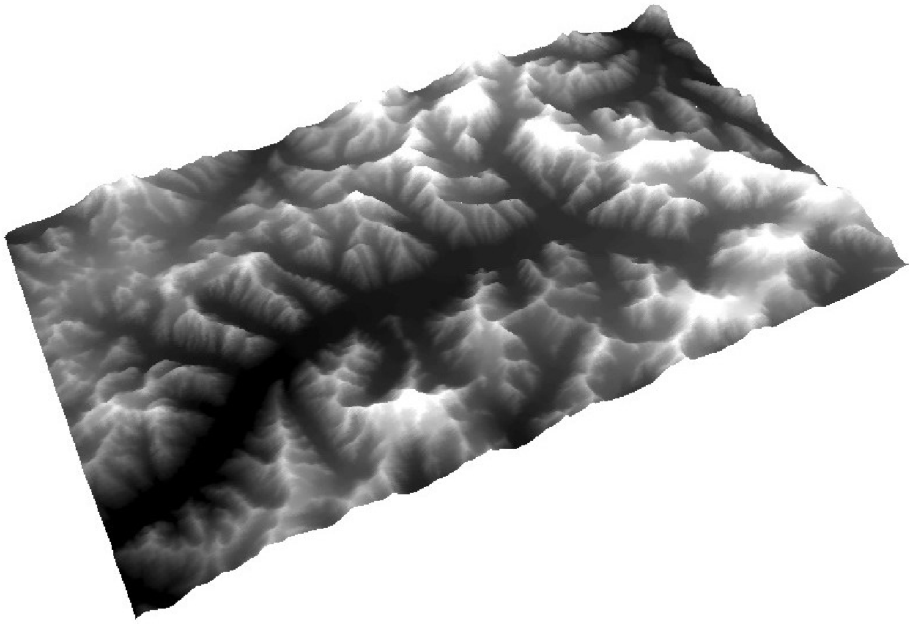
APPENDIX 1(F): SCENE OF LANDSAT-7 TM OF BIAFO GLACIER (1998)



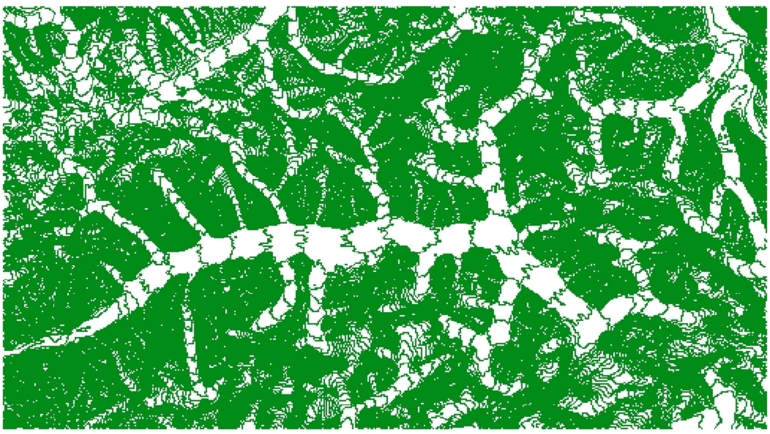
APPENDIX 2(A): BAND RATIO RESULTANT OF BALTORO GLACIER

APPENDIX 2(B): RESULTANT OF SHAPE FILE OF BALTORO GLACIER

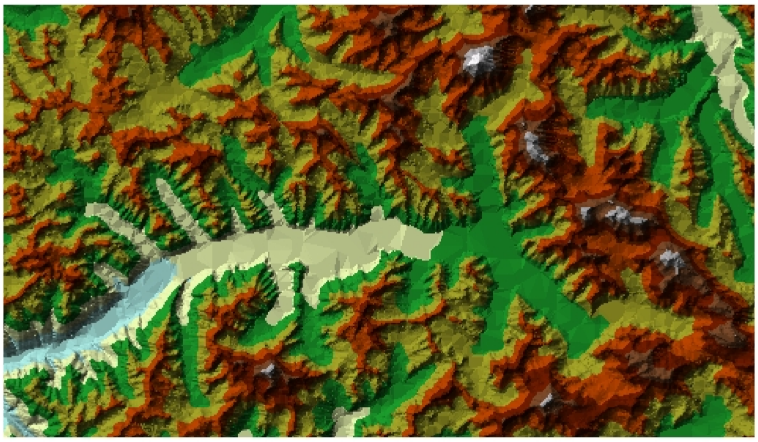
APPENDIX 2(C): DIGITAL ELEVATION MODEL OF BALTORO GLACIER



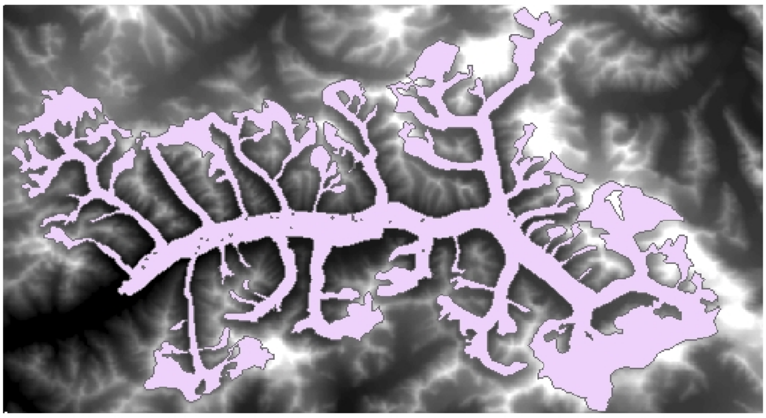
APPENDIX 2(D): DIGITIZATION OF CONTOURS OF BALTORO GLACIER



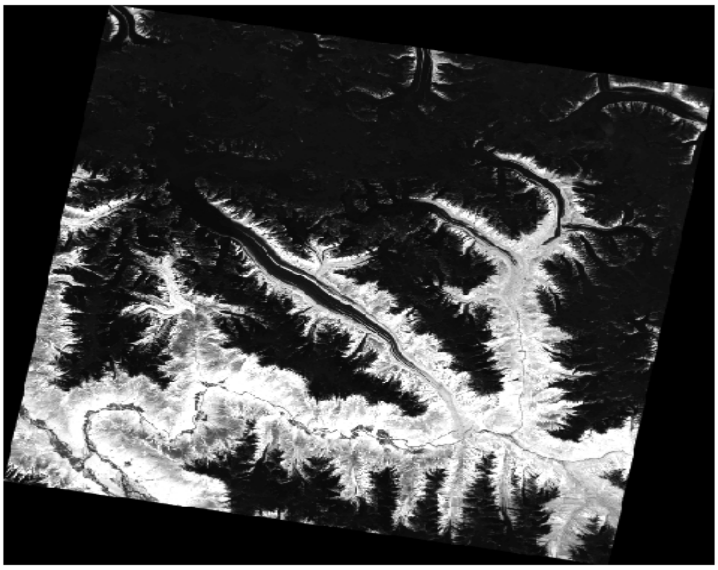
APPENDIX 2(E): SRTM DATA OF BALTORO GLACIER



APPENDIX 2(F): EXTRACT BY MASK OF BALTORO GLACIER

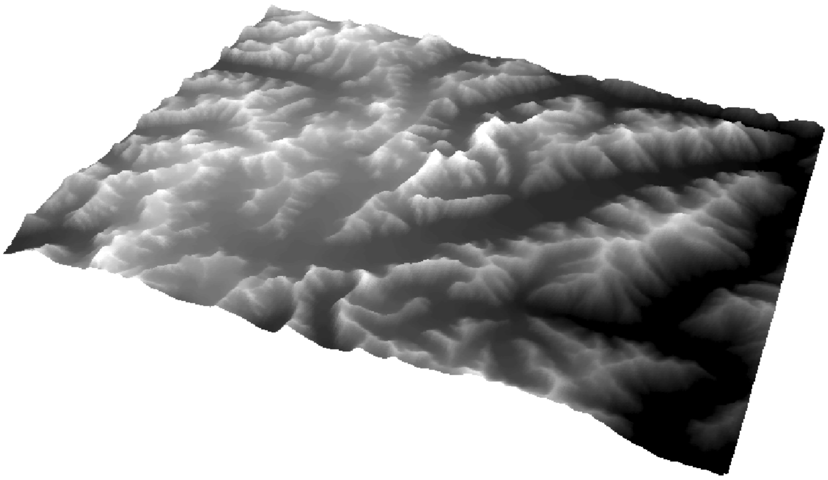


APPENDIX 3(A): BAND RATIO RESULTANT OF BIAFO GLACIER

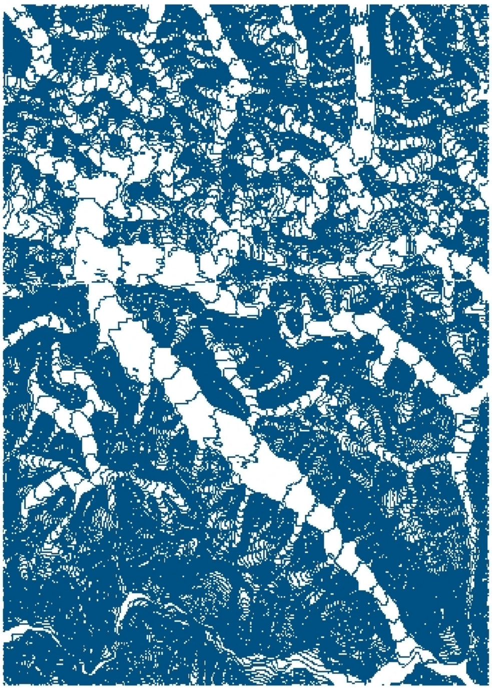


APPENDIX 3(B): RESULTANT OF SHAPE FILE OF BIAFO GLACIER

APPENDIX 3(C): DIGITAL ELEVATION MODEL OF BIAFO GLACIER

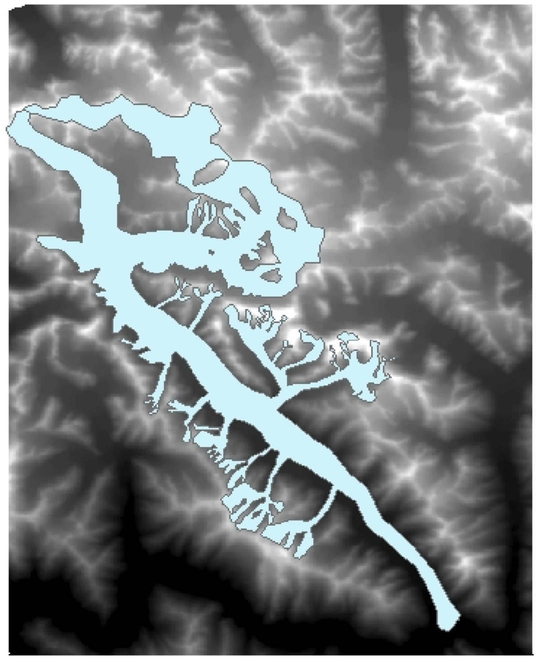


APPENDIX 3(D): DIGITIZATION OF CONTOURS OF BIAFO GLACIER

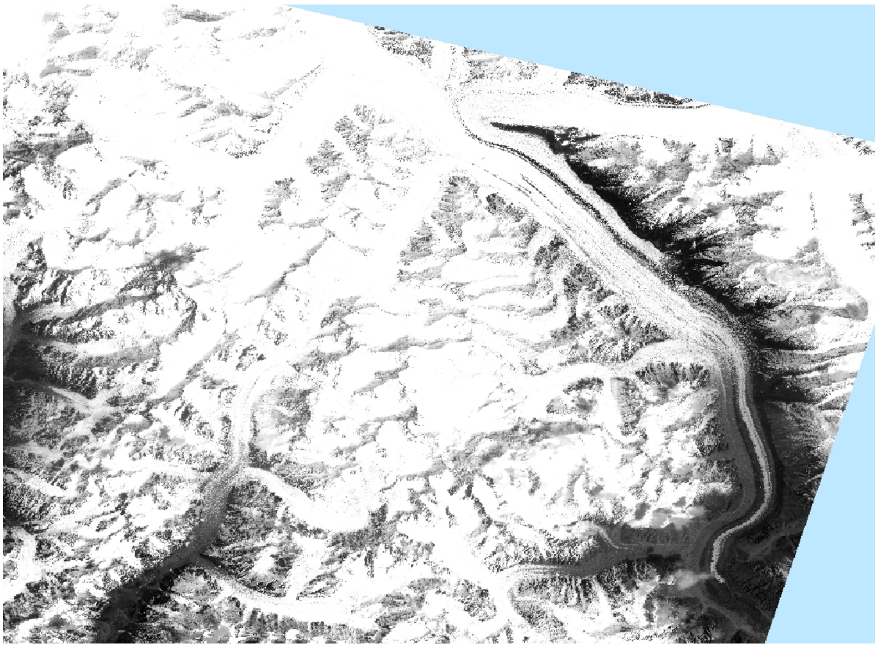


APPENDIX 3(E): SRTM DATA OF BIAFO GLACIER

APPENDIX 3(F): EXTRACT BY MASK OF BIAFO GLACIER

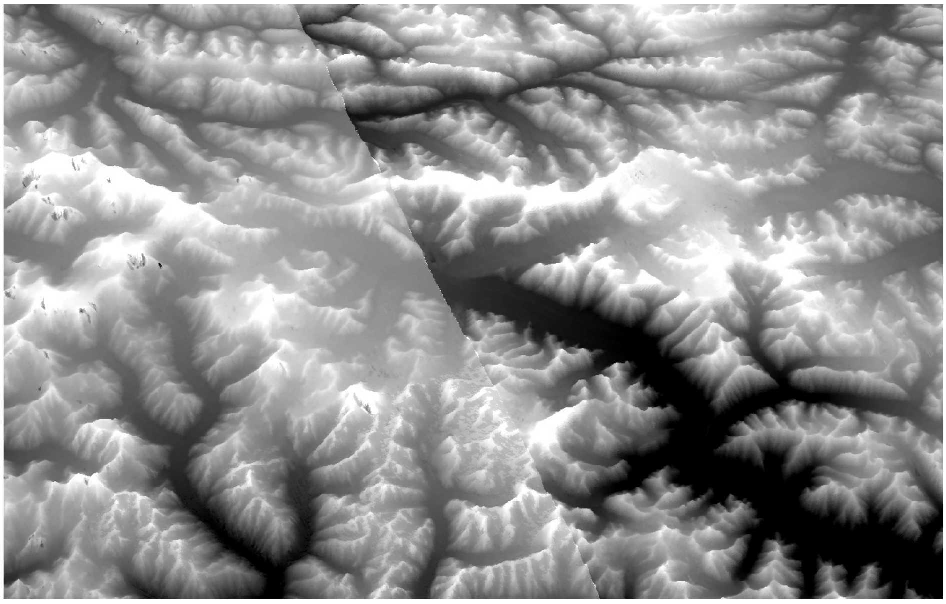


APPENDIX 4(A): BAND RATIO RESULTANT OF SIACHEN GLACIER

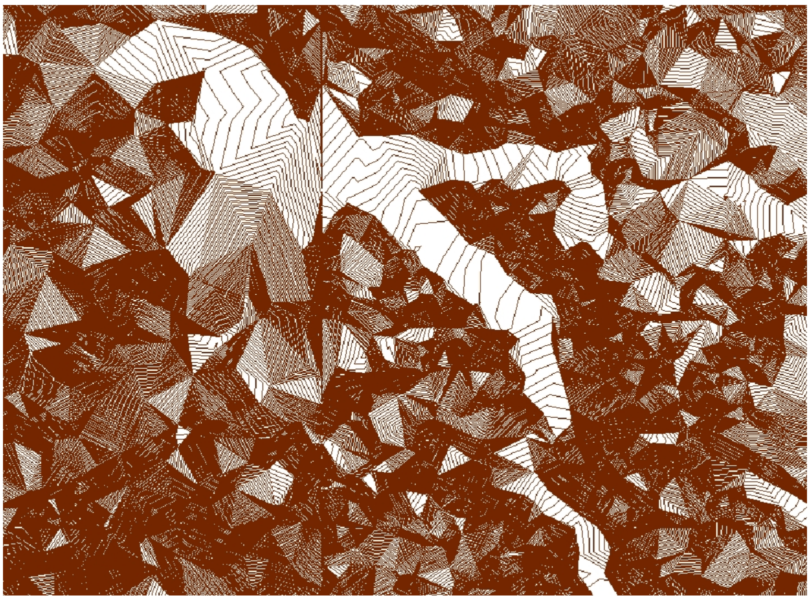


APPENDIX 4(B): RESULTANT OF SHAPE FILE OF SIACHEN GLACIER

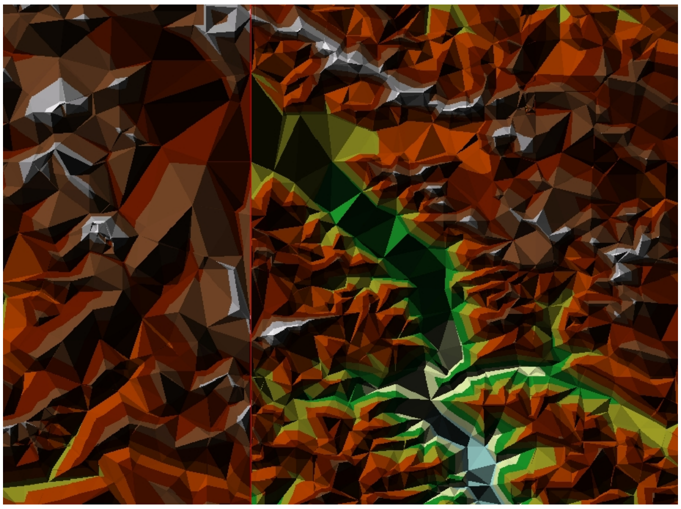
APPENDIX 4(C): DIGITAL ELEVATION MODEL OF SIACHEN GLACIER



APPENDIX 4(D): DIGITIZATION OF CONTOURS OF SIACHEN GLACIER



APPENDIX 4(E): SRTM DATA OF SIACHEN GLACIER



APPENDIX 4(F): EXTRACT BY MASK OF SIACHEN GLACIER

ACRONYMS

ADRG	ARC Digitized Raster Graphics
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
DMA	Defense Mapping Agency
ERTS	Earth Resources Technology Satellite
TM	Thematic Mapper
FCNA	Force Comd Northern Authority
FPSP	Flood Protection Sector Study
FWC	Flood Warning Centre
Ha.	Hectares
HKH	Hindukush-Himalaya-Karakoram
IBIS	Indus Basin Irrigation System
LANDSAT	Land Resources Satellite
NIMA	National Image and Mapping Agency
PMD	Pakistan Meteorological Department
SRTM	Shuttle Radar Topographic Mission
SUPARCO	Space and Upper Atmospheric Study Commission
WAPDA	Water and Power Development Authority
WECS	Water and Energy Commission Secretariat
XS	Multispectral Mode Sensor System (SPOT)