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GEOSPATIAL ANALYSIS OF GLACIAL HAZARD PRONE AREAS OF SHIGAR AND SHAYOK BASINS

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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. Assessment of glacial hazard is carried out in this research using Satellite and Topographic data.

About 5,218 large and small glaciers cover a glaciated area of 15,040 km^2 and ice reserves of 2,738 km^3. The Shayok, Hunza and Shigar basins contain the major part (83%) of ice reserves.

This research presents the glacial hazard computations of largest glaciers of Pakistan. The results computed through study are compared with mathematical model of ice reserves and ice thickness which has supplemented their validity. The correlation of glacial hazard of these glaciers with average temperature rise of northern areas is confirmed.

The location of a site, snow cover/ melting behavior of the glacier, slope/ aspect of glacier, geo-morphology of the rocks and glacier dynamics are taken as indicators of disasters in the form of avalanches, snow/ land slide and glacier breakdown in the form of debris along with rock material.

The percentage degree of risk of glacial hazard is computed, which indicates that three out of world's seven largest glaciers have experienced degradation / volume loss over the years subjected to host of factors including anthropogenic activities.

For analysis, various methods of image classification in visible and thermal bands are used. The DEM is incorporated to detect the indicators of hazard as slope, orientation and glacier mass balance of the glaciers overlooking the settlements. The results show that settlements are found threatened by disastrous events of glacial activity which is further reconfirmed during the field visits.

KEYWORDS: Global Warming, Glacial Hazard, Settlements, Anthropogenic, Geo-morphology.

1 INTRODUCTION

GENERAL

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 20^{th} century and have contributed to the formation of many glacial lakes on the recent glacier terminus (Mool et al., 2001).

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 Shayok, Hunza and Shigar basins contain the major part (about 83%) of these ice reserves. In this research, the areas of interest are located in Shayok and Shigar basins.

PURPOSE OF RESEARCH / JUSTIFICATION

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 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.

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. 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. 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). 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.

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. 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. 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). 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.

HYDROMETEOROLOGY

The hydrometeorological 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.

a. **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, Shayok 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.

Figure 1.1: Glaciated river basins of northern Pakistan.

b. **Shigar River Basin**

(1) 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.

(2) 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.

(3) 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.

c. **Shayok River Basin**

The Shayok River 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.

There are 372 glaciers which contribute to a vast glacier area of about 3,548 sq. km. Though the Valley glaciers are only 14 % of the total number, they contribute more than 82 % to the glacier area. This high contribution is mainly due to larger area of the individual glaciers. Some of the important Valley glaciers shown in include Siachen, Kondus, Bilafond, Chogolisa, Ghandogoro and Masherbrum.

The glacier area of the basin contributes to about 892 km^3 of the total ice reserves of the basin. Again the major source of this huge ice reserve is the Valley glaciers which contribute more than 94%.

Aspect wise the basin has been divided into various ordinal directions. Glaciers are oriented towards NE (29%), NW (24%) and E (18%) but are absent on the western aspects.

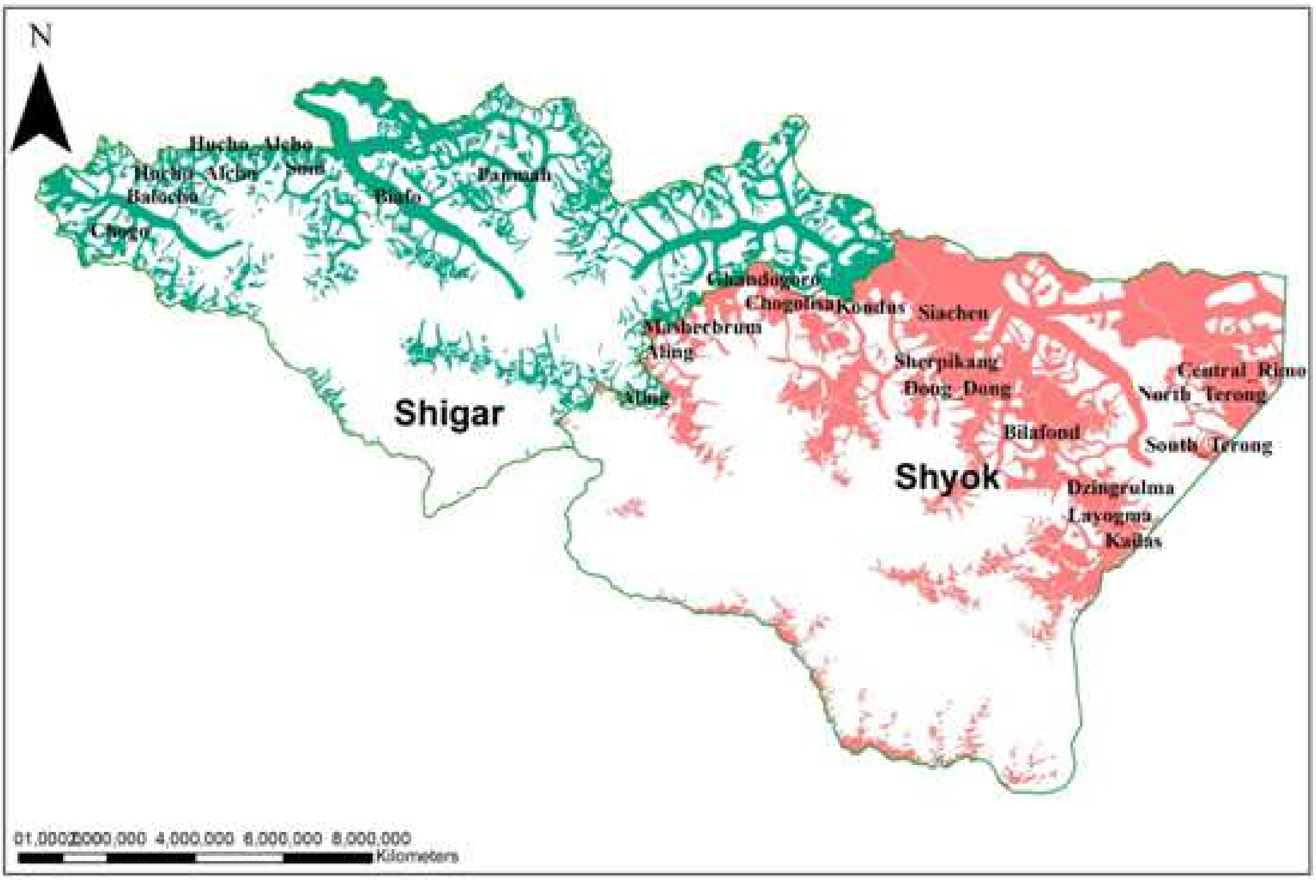

Figure 1.2: The distribution of glaciers in Shigar and Shayok basins.

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). Three out of seven world's largest glaciers are present in the northern areas of Pakistan making its geographic location prime in the region.

STATEMENT OF THE PROBLEM

The melting ice is a manifest of global warming. Alpine Glaciers are subjected to the climate change, which is a consequence of terrestrial heat flux. This research has resulted in determination of Glacial Hazard in Shigar and Shayok basins in relation with temperature rise in northern areas and rise in anthropogenic activities.

OBJECTIVES OF RESEARCH

The prime objective of this study is to assess the glacial hazard of glaciers of Pakistan. The secondary objectives are as following:

a. Identification of hazard prone areas in Shigar and Shayok basins pertaining to glacial activity for declaration of high risk areas by formulation of Risk Index (%).
b. Estimation of three major glaciers depletion.
c. Correlation of snow coverage depletion with average annual temperature rise in northern areas of Pakistan.
d. GIS based identification of suitable alternate locations keeping in view the qualitative risk mitigation.

SCOPE OF 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.

2 LITERATURE REVIEW

GENERAL

Earth surface is unique in characteristics it possesses in the form of land cover. 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.

The warming of the atmosphere caused by increases in greenhouse gases is melting glaciers. 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).

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.

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).

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

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

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. 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. This seems to be a further reason to give more attention to surging glaciers as the glaciers fluctuation is subjected to terrestrial heat flux.

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 subjected to 2 km retreat during the last two decades which is the max retreat in the vicinity.

The Siachen glacier is having following characteristics:-

Parameters	**Value**
LENGTH	76641 m
ASPECT	SE
AREA	1056.42 $(Km)^2$
THICKNESS	418.35 m
RESERVE	441.96 $(Km)^3$
LAT	35°33'27.83" N
LONG	76°54'29.49" E

Table 2.2: Parameters of Siachen glacier situated in Shayok river basin.

Figure 2.1: Siachen glacier retreat (2 km in 2 decades).

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 Shayok, Shigar, Hunza, Astor, Gilgit, Ishkuman, Yasin, Ghizer, Yarkhun, Rich Gol, Arkari, Kunar, Panjkora, and Swat rivers which are fed from these glaciated basins.

3 MATERIALS AND METHODS

GENERAL

The basic materials required for the compilation of glacial hazard assessment of glaciers are high quality topographic maps and temporal high resolution satellite data. The remote sensing data of land observation satellites e.g, LandSat, SPOT, and ASTER is 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 is used for better and more accurate results for the computation of glacial hazard assessment 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 Biafo Glacier, Baltoro Glacier and Siachen Glacier which spread over an area of 72,496 km^2 and are reported to be melting fast.

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

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

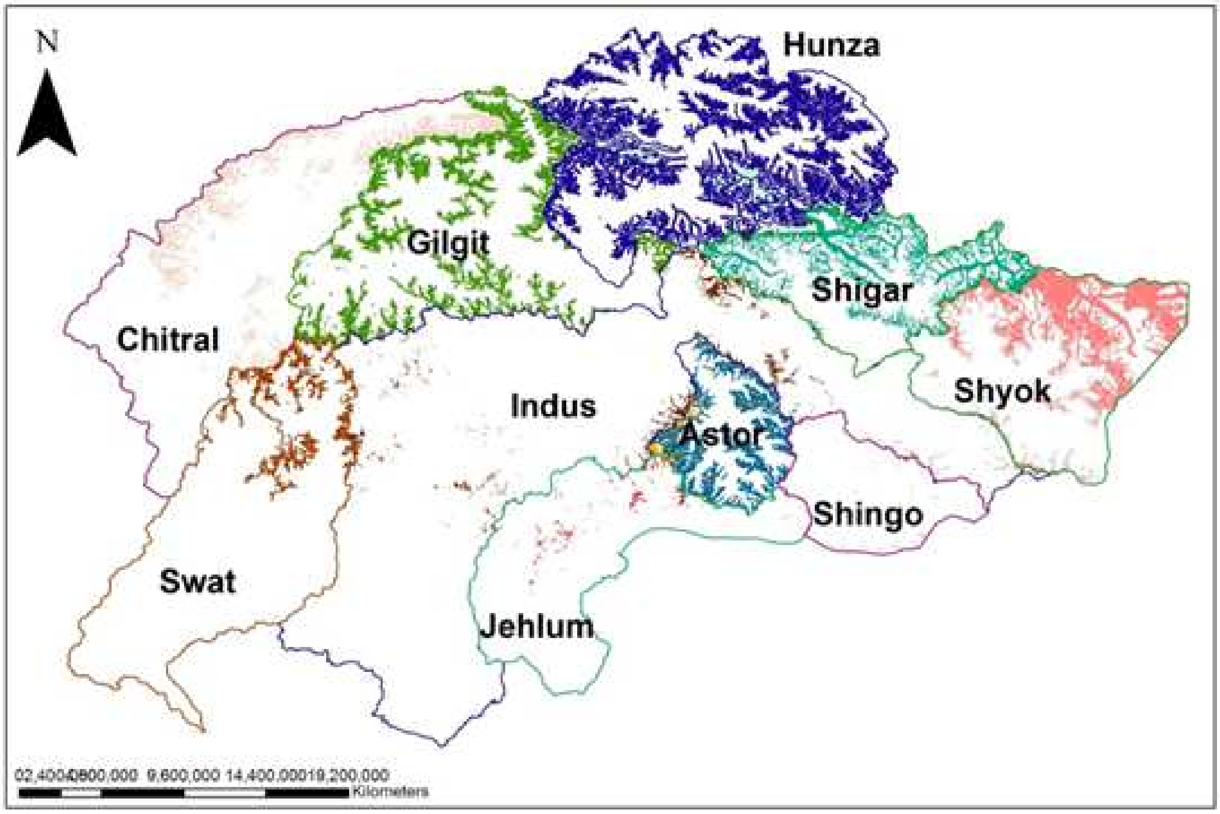

Figure 3.1: Distribution of glaciers in river basins of northern Pakistan.

DATA SETS

Following data set is used for the purpose of this research:-

a. SPOT Images of Baltoro, Biafo and Siachen glaciers of northern Pakistan within the time span of last decades obtained from SUPARCO.
b. ASTER multispectral Images of Shayok and Shigar basins of northern Pakistan within the time span of last decades.
c. Digital elevation models of Baltoro, Biafo and Siachen glaciers from SRTM data of year 2000, latest release of ASTER GDEM and topographic maps of Survey of Pakistan.
d. Meteorological data including average annual temperature record of northern areas of Pakistan during the last decades obtained from Pakistan meteorological department.
e. Geomorphologic data of northern areas of Pakistan obtained from geological Survey of Pakistan.

TOPOGRAPHIC MAPS

The glaciers are mostly concentrated in the north. The river basin boundary and spatial distribution of glaciers is identified from the satellite images and supplemented with the available topographic maps at scale of **1:250,000**. The topographic maps (42L, P, 43M, 52A) 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.

SATELLITE IMAGE

The remote sensing data of LandSat, SPOT and ASTER is used for the spectral differentiation / delineating the boundary of the glaciers. The image data are in digital format and have a pixel size of 30 m and 15 m respectively for analysis of the Baltoro, Biafo and Siachen glaciers out of the two river basins Shayok and Shigar of northern areas.

SOFTWARE

a. ERDAS IMAGINE.
b. ArcGIS.
c. Land Serf.
d. Global Mapper.
e. ENVI.
f. S-Plus.

DIGITAL ELEVATION MODEL

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

MEAN GLACIER THICKNESS AND ICE RESERVE

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

The data based on different geophysical techniques available for the measurement of glacial ice thickness in the northern parts of Pakistan is available for only selected glaciers. To supplement the research results the mathematical model of ice thickness and ice reserves is incorporated. The relationship between ice thickness (H in m) and glacial area (F in km^2) is obtained there as:

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

This formula is 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 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 orientation of accumulation and ablation areas is represented in eight cardinal directions (N, NE, E, SE, S, SW, W, and NW). The glaciers identified and mapped in the satellite images are also mapped in the available topographic maps, therefore in this research the elevation of the glaciers is considered for both the datasets involving the contours of topographic sheets (1990) and point data of SRTM (2000).

IMAGE PROCESSING

The LandSat, SPOT and ASTER images are acquired from SUPARCO, after georeferencing the desired Area of Interest (AOI) is extracted. Moreover the topographic maps are scanned and after georefrencing, all are digitized to get GIS layers for analysis.

a. The Sat images are processed and georeferenced.
b. Aspect and Slope maps are generated using height information extracted through DEMs.
c. Identification of Glaciers, GLOFs and Glacial hazard areas are carried out through geospatial analysis.

METHODOLOGY

The study and acquisition of literature, topographic maps and satellite images for capturing the digital data of glaciers arecarried out in first phase. Thereafter from maps and SRTM data the digital elevation models aregenerated for analysis of volumetric decrease / depletion of Baltoro, Biafo and Siachen glaciers in order to assess the glacial hazard in Shiger and Shayok basins. Finally the correlation with anthropogenic activities in this vicinity of northern areas for computation of glacial hazard to the settlements arecarried out. The methodology adopted in this research is shown in a flow chart (Figure 3.2).

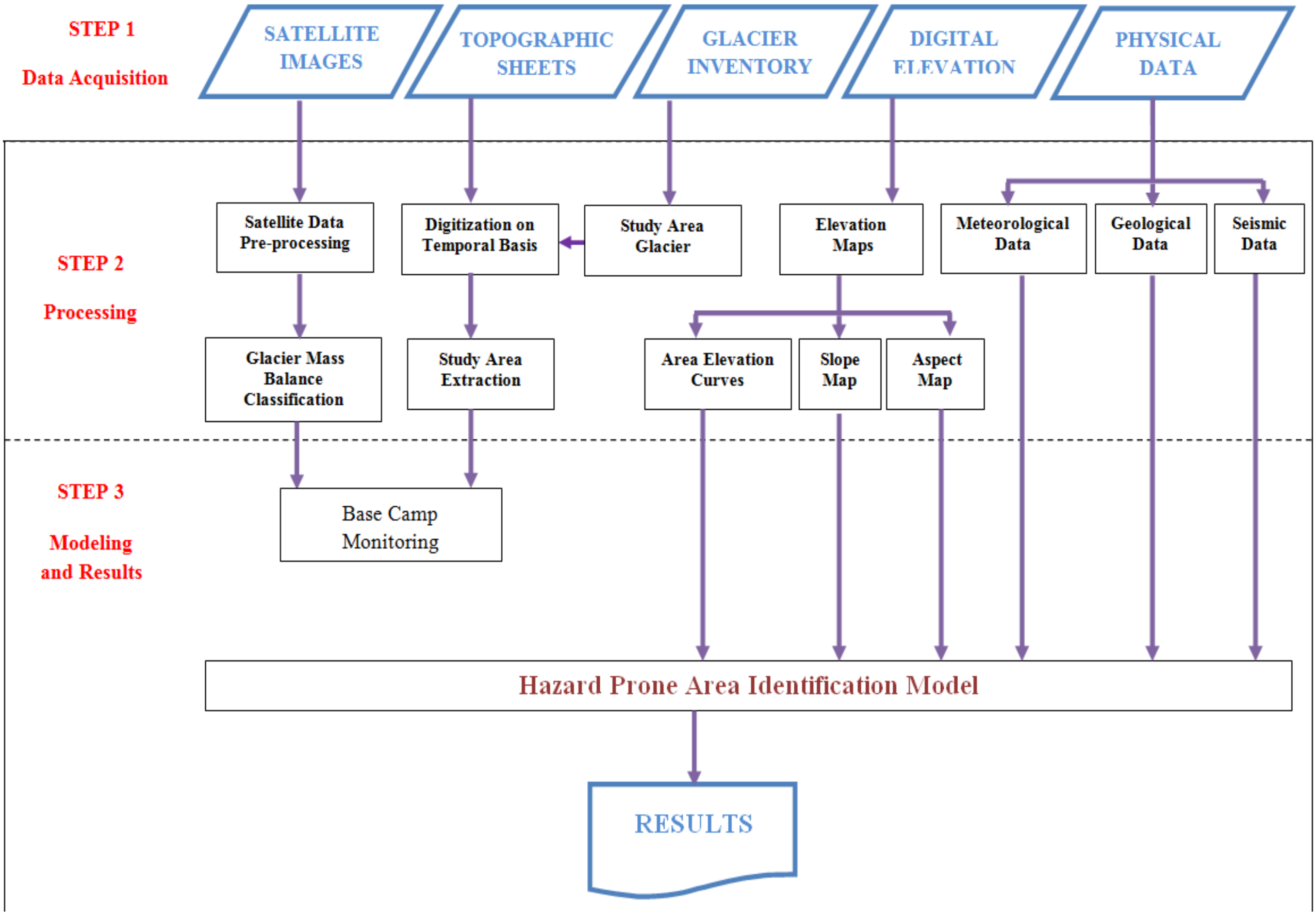

Figure 3.2: Methodological flow chart of geospatial analysis of glacial hazard

4 Results And Discussions

General

The objectives of this research 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 depletion of the important glaciers of northern Pakistan during last decades, spatial distribution of the glaciated areas, and correlation with anthropogenic activities in northern areas of Pakistan to map the glacial hazard extents.

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 Himalyas. The snow and ice cover of the upper Indus River basin undergoes large spatial as well as temporal variations. The glaciers in Karakoram region are high activity glaciers and have some of the steepest gradients in the world.

The figure 4.1 shows the annual rate of change in the ice elevation over the Northern areas. Majority of the Glaciers in Northern areas are with negative thickness change especially at the tongues of the glaciers.

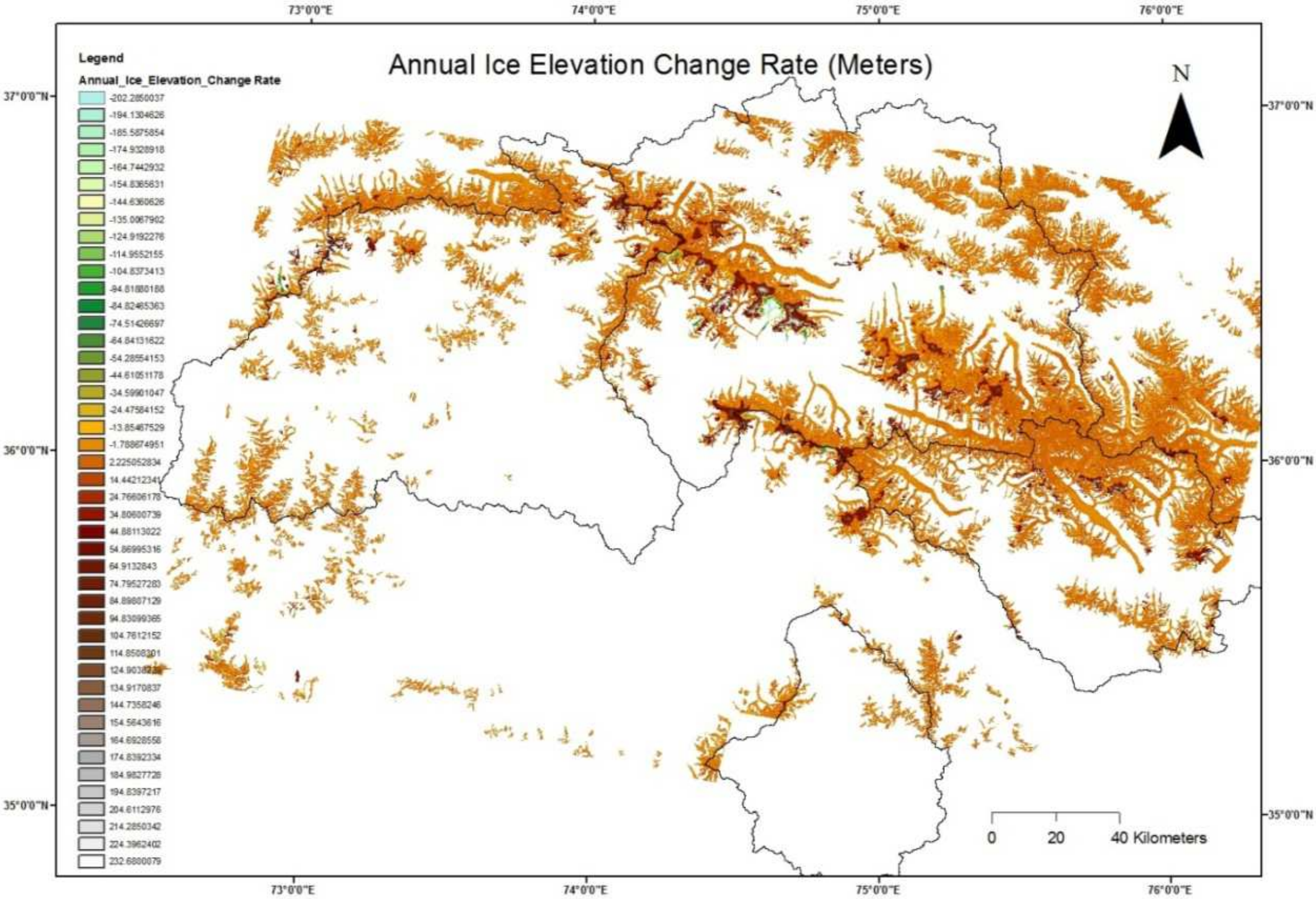

Figure 4.1: Annual ice elevation change rate of glaciers of northern areas.

HAZARD PRONE AREAS IDENTIFICATION

High risk areas are identified in Shigar and Shayok basins where settlements are exposed to:-

a. Land slides
b. Avalanches
c. Flash flooding (Glacial Lake Outburst Floods)
d. Climatic conditions
e. Snow storms

These risks are being faced by the spatial locations of settlements, various installations as well as the surrounding areas. Slope and Aspect of various glaciers as well as the surrounding areas (both snow and ice covered peaks and valleys) owing to their exposure to solar radiations, snow accumulation, ice accumulation and formation of crevices in ice, conversion of ice into debris especially in lower peaks of the mountains, formation of glacial lakes and water bodies in glaciated areas due to changing climatic conditions together with anthropogenic activities and lastly the geomorphologic features are the host of factors contributing towards glacial hazard.

GLACIAL HAZARD ANALYSIS

Glaciers experience a substantial retreat and the duration of snow cover is expected to decrease substantially for each °C of temperature increase at mid elevations (Bundesministrium, 2003).

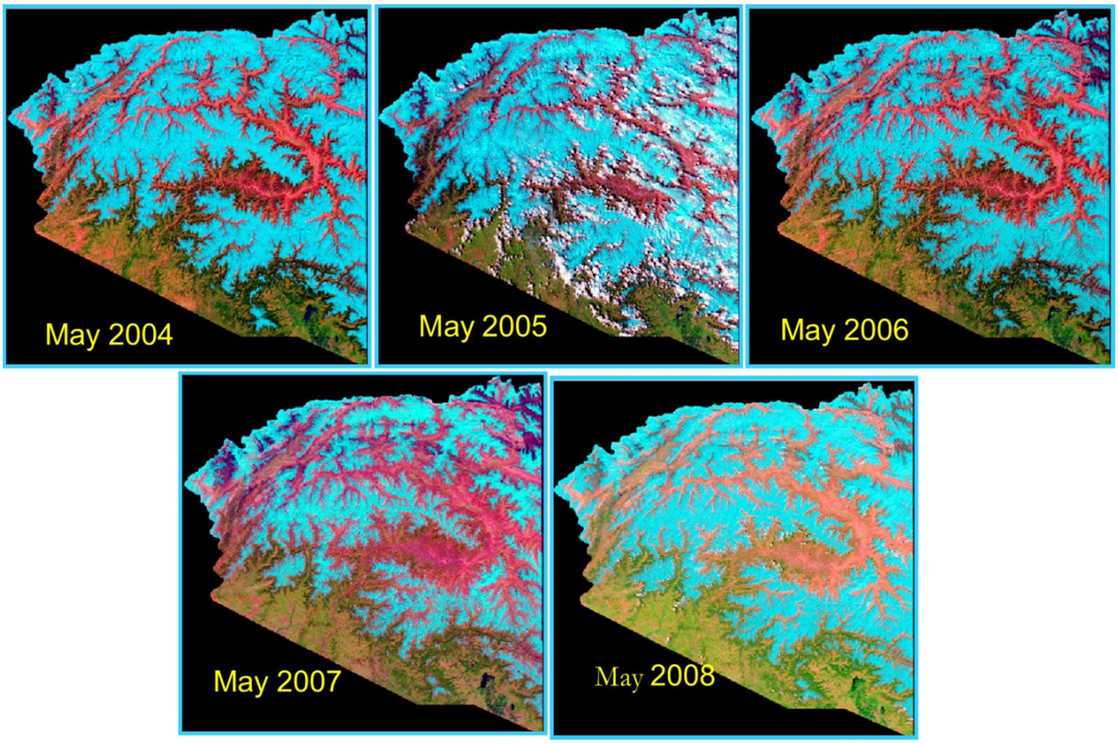

Figure 4.2: Depletion of glaciers in Pakistan from 2004 – 2008.

Glaciers 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. Glacial hazard prone areas in the vicinity are at high risk.

GLACIAL HAZARD RISK INDICATORS

The glacial hazard risk indicators e.g, Location, Elevation, Slope, Aspect, Retreat and Geomorphology of a particular site determine the description of risk.

Indicators	Description of Risk
Location	Location of a settlement (**Glaciers** with abrupt changes in melting rates are dangerous)
Elevation	Direct relation with the **probability of occurrence** and its magnitude
Aspect	The **SE is more prone** to disasters as it endures more solar radiation causing depletion
Slope	Literature shows a slope between **30 – 45 %** are prone to glacial hazards such as avalanches and slides
Geomorphology	Type of **underneath surface** and parent material
Geo Cover	Heavily forested areas are much safer than **open spaces**
Crevasses	Deeper crevasses help snow/ice accumulation which may **burst out in response to a slight change** in parameters
Snow / Ice melting of Glacier	Glacial hazards such as **GLOF** (Glacial Lake Outburst Flood), avalanches, or landslides are triggered by abrupt glacial melt

Table 4.1: Glacial hazard risk indicators.

RISK INDEX

The risk Index factor is assigned based on parameters like Location, Elevation, Slope, Aspect, Retreat and Geomorphology of a particular site. The degree of threat is assigned based on these parameters. Further on the basis of calculated indicators of glacial hazard, the % degree of risk are calculated by using the following equation:-

$$\% \text{ Degree of Risk} = \frac{\textit{No.of disaster indicator falling in danger criterion}}{\textit{Total number of studied indicators}} \times 100$$

Qualitative Degree of Risk	Degree of Risk (%)	Parameters	Remarks	Probability
Dangerous	80-100	Location, Elevation, Slope, Aspect, Retreat, Geomorphology	Re Location	High
Very High	60-80	----	Re Adjustment	High
High	40-60	----	Continuation at High Risk	Medium
Moderate	20-40	----	Continuation at Moderate Risk	Medium
Low	0-20	----	May Cont	Low

Table 4.2: Probable outcome based on risk index.

SHAYOK RIVER BASIN

The Shayok 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.

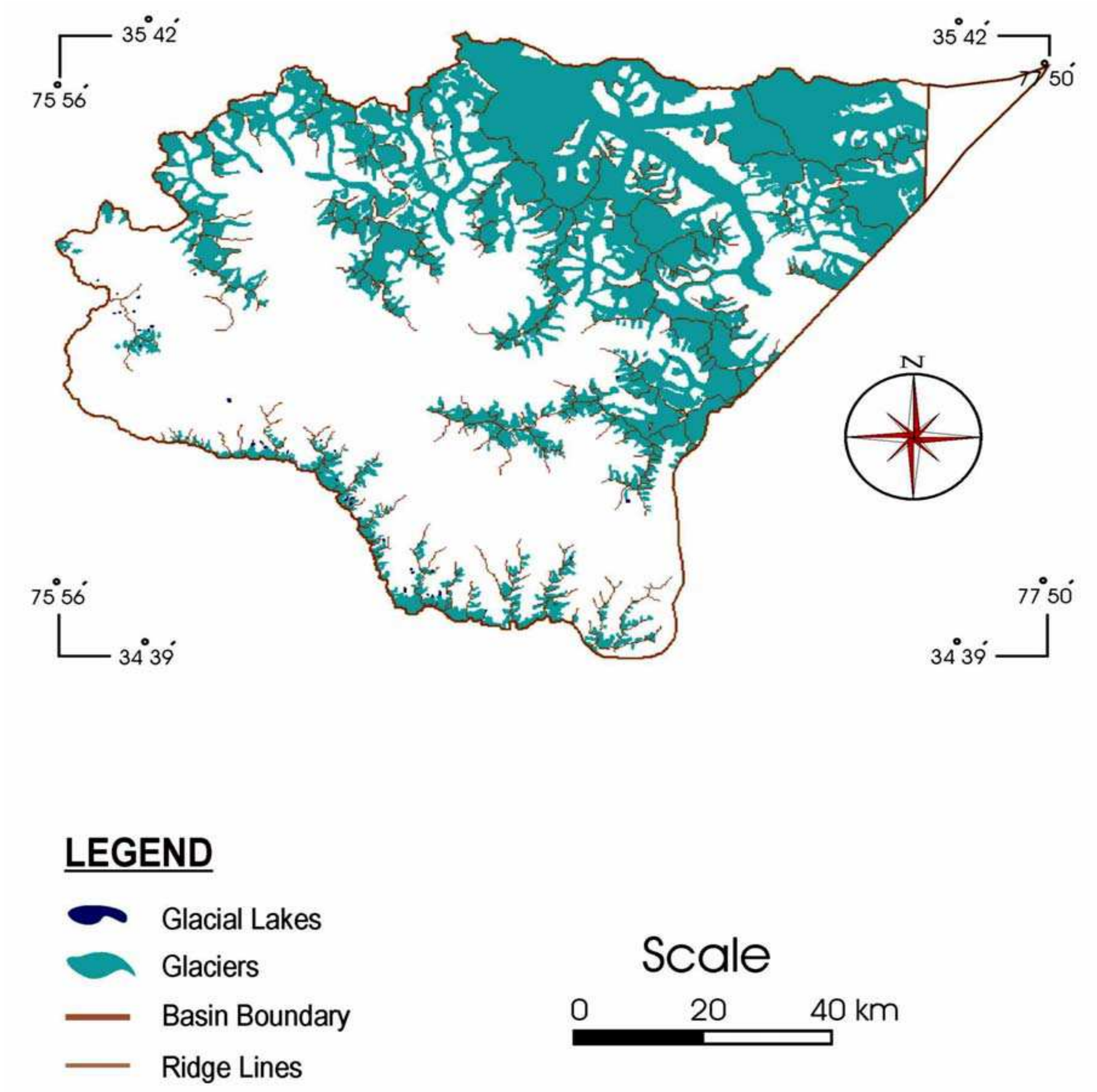

Figure 4.3 : Glaciers distribution in Shayok river basin.

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.

a. Aspect Wise Snow Coverage of Shayok Basin

(1) 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.

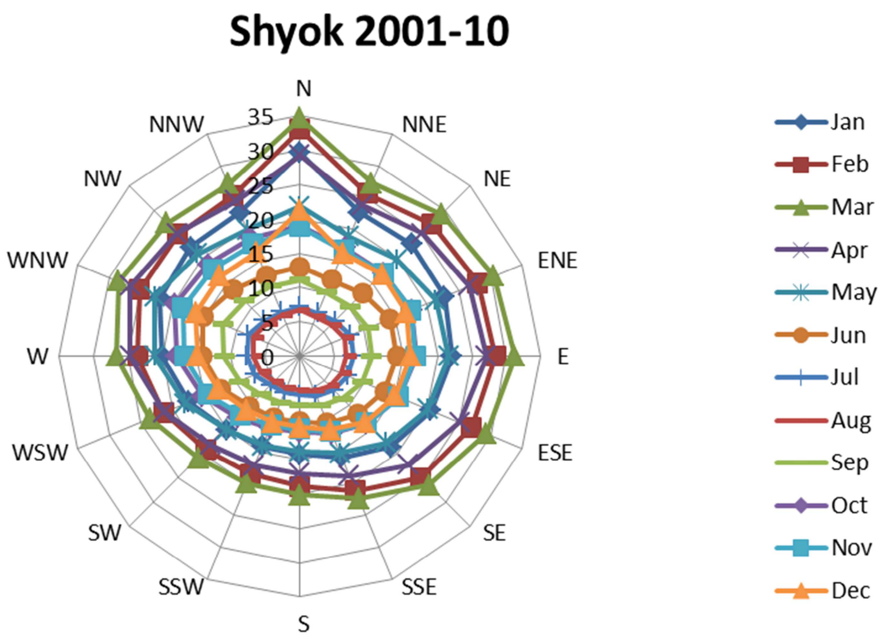

Figure 4.4: Aspect wise snow coverage in km of Shayok basin.

(2) 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.

SETTLEMENT

Settlement situated near snout of glacier at a height near 14000 ft. The location is prone to disaster from a possible glacial mass movement / debris flow. The glacier containing debris and rock fragment may prove catastrophic cause of a cloud burst.

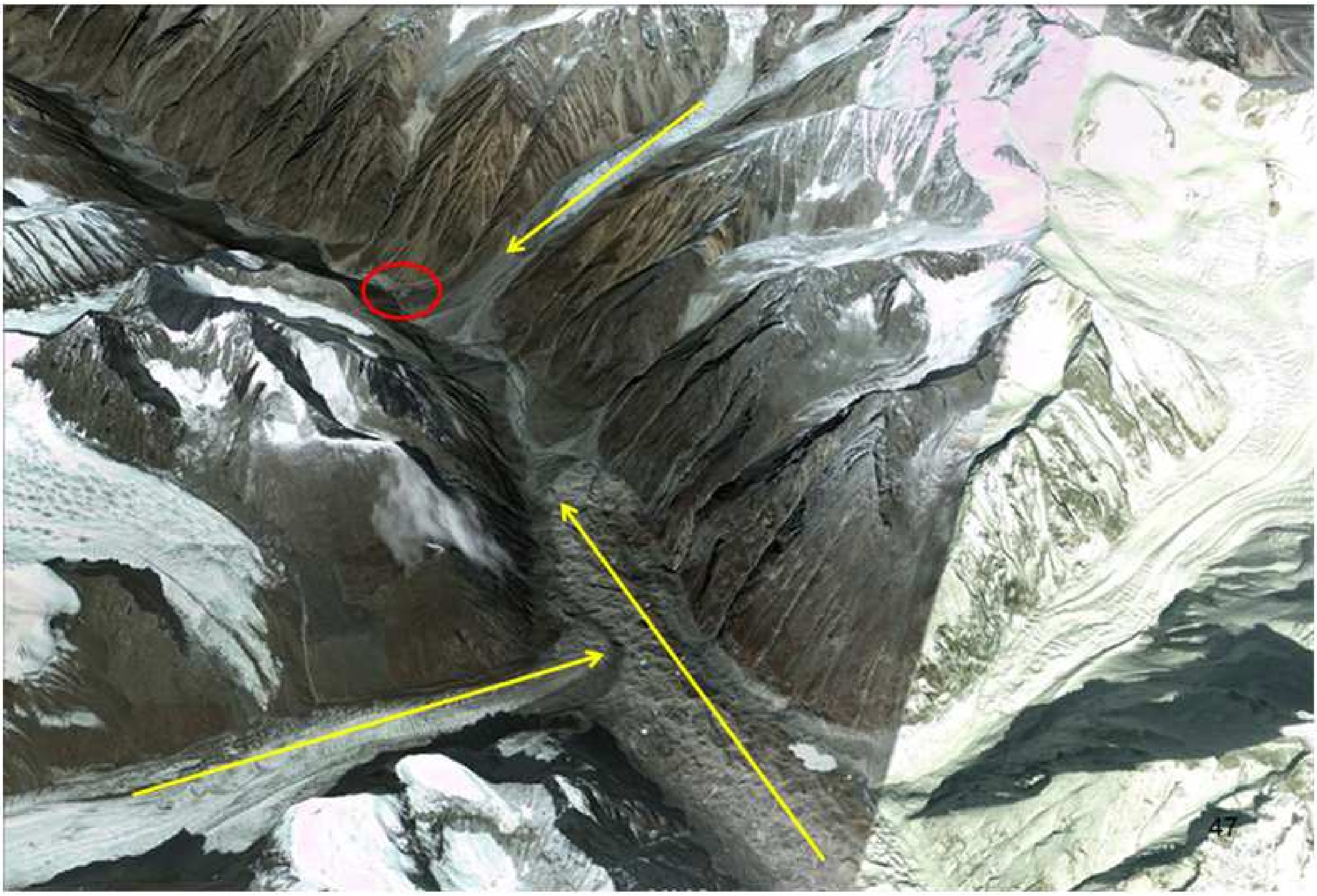

Figure 4.5: Glacial hazard to settlement.

DETERMINATION OF GLACIAL HAZARD RISK INDEX

a. The glacial hazard risk index are determined by aggregating the degree of risk for certain parameters like location, elevation, slope, aspect, retreat and geomorphology of a glaciated area.

b. **Location**

The location of glacier terminus / snout approaching settlement site. Although glacier seem motionless to the observer, in reality glacier is in endless **motion** and the glacier terminus is either advancing or retreating. The location of the terminus is directly related to **glacier mass balance**, which is based on the amount of snowfall which occurs in the **accumulation zone** of a glacier, in comparison to the amount that is melted in the **ablation zone**. The position of a glacier terminus is impacted by localized / regional temperature change over time posing threat to the settlement.

c. **Elevation**

The elevation of settlement nearest glacier makes it vulnerable. All the time it's cold at 18,000 feet and above. Globally, the prognosis for glaciers is dismal. At elevations below 14,000 feet the Himalayan Alps are melting, and that the same is true throughout the region. Antecedent, the low elevation of the glacier pose threat to the settlement site as depletion of glacier can cause catastrophic.

d. **Aspect**

The orientation of the glacier surface with respect to incoming solar radiation, or aspect, e.g, SE which is particularly important on account of depletion, in area of Shayok alpine glaciations, i.e, on the mid latitudes. The smaller glaciers are particularly more impacted by the aspect. The sloping surface facing the sun receives much more solar radiation than if that same surface were flat. There is generally a melting of glaciers and lowered snowlines towards the southeast slopes, thus the glacier aspect being SE to S causes a major hazard to settlement as of being more pronounced aspect to solar radiation.

e. **Slope**

Alpine glaciers are found only where snow has room to accumulate to a large enough mass. Because of this, glaciers have a preference for peaks that have wide plateau areas. Steep, precipitous peaks tend to have less of a snow cover, because the snow is unable to pile up on the steep slopes. If a highland area is dissected into many steep slopes, avalanches redistribute snow to the valleys, and glaciers are confined to these gentler slopes. The glacier having more than 30 % slope encompasses hazard of avalanche triggering. The settlements nearest glacier having their slope more than 30 % make them more prone to avalanche trigger once coupled with geothermal gradient cause of global warming.

f. **Geomorphology**

Geomorphology of the glaciers dictates the underlying **bedrock topography**. **Valley glaciers**, which provide drainage for ice fields, are also constrained by underlying topography. Ice-free exposed bedrock and slopes often surround valley glaciers, providing snow and ice from above to accumulate on the glacier via **avalanches**. The area is tectonically active as the main karakoram thrust (MKT) passes nearby. The impact of regional geodynamics and local tectonics dictate generation of glacial hazard to the settlements if nearest glaciers is posing threat of alluvial fan.

GLACIAL HAZARD RISK INDEX FOR SETTLEMENT

The degree of glacial hazard risk index of the settlement site are determined based on certain parameters as following:-

Parameters	Weight	Remarks
Location	20%	
Elevation	20%	
Aspect	20%	
Slope	20%	
Geomorphology	20%	

Table 4.3: Glacial hazard risk index for settlement site.

On the basis of the above table it are concluded that all the studied indicators of disaster fall in the dangerous criteria or otherwise. Therefore according to equation of degree of risk, the max degree of risk is as follows:-

$$\% \text{ Degree of Risk} = 5/5*100 = 100\%$$

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 4.6). The elevation range varies from about 2,500 m to more than 8,600 m.

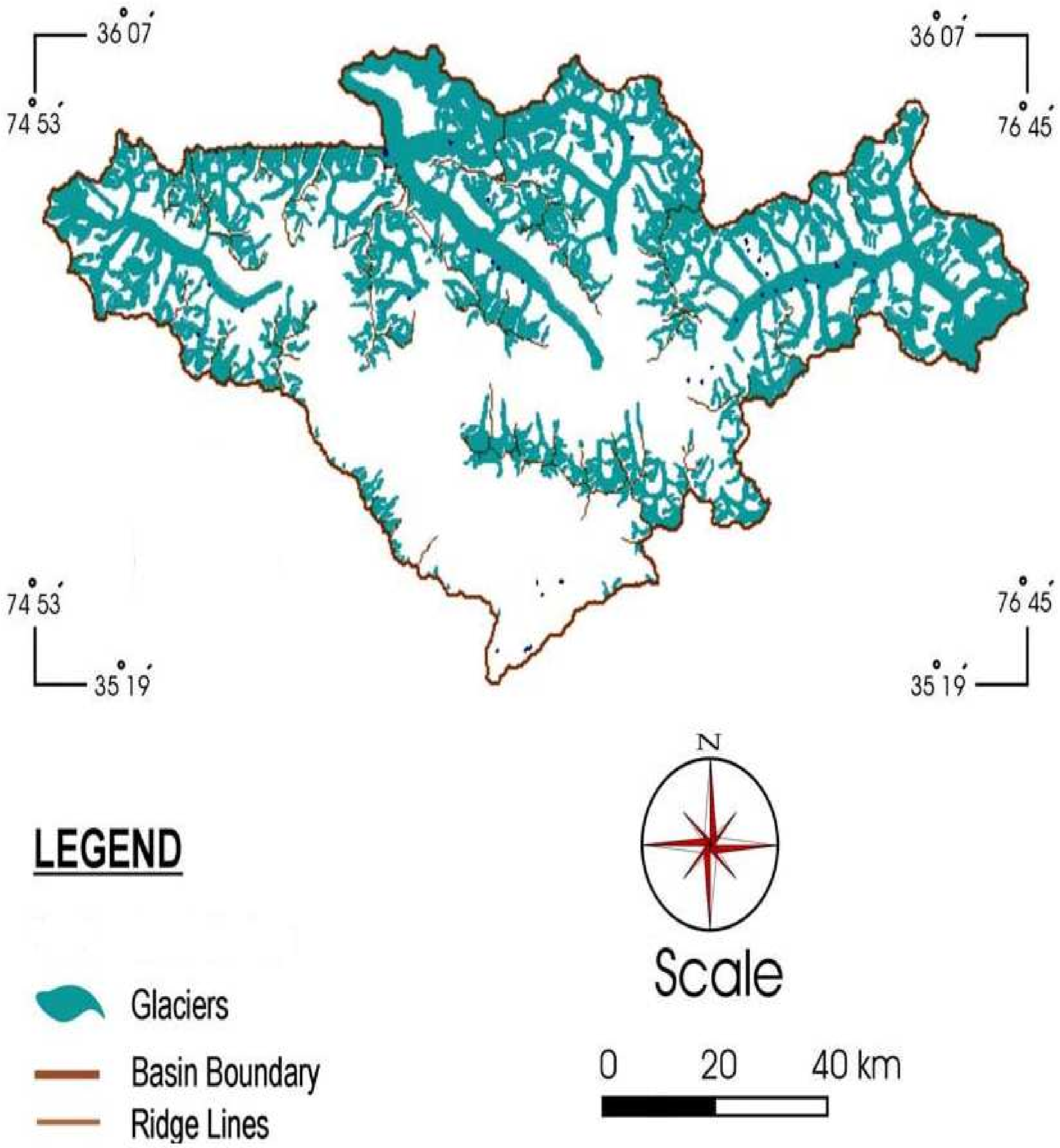

Figure 4.6: The glacier distribution in the Shigar river basin showing Baltoro and Biafo glaciers significance in the region being the largest.

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 (4.6). 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.

a. **Aspect Wise Snow Coverage of Shigar Basin**

(1) 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.

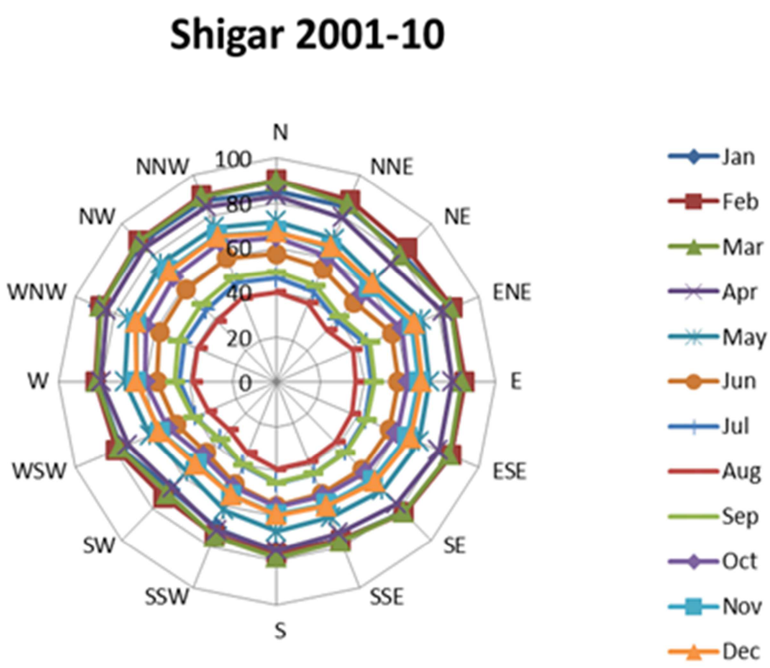

Figure 4.7: Aspect wise snow coverage in km of Shigar basin.

(2) The fig 4.7 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 4.7. 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.

PROBABILITY OF AVALANCHE TRIGGER / GLACIAL HAZARD OCCURRENCE

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. Alpine glaciers had already lost more than 25% of their volume in the 50 years (Bundesministrium, 2003). The estimated total glacier volume loss in the alpines during the decade of 1990-2000 is 5-10% of the remaining ice volume. As with 1.78 ^{o}C temperature rise, the average volumetric decease of Baltoro, Biafo and Siachen glaciers during the decade of 1990-2000 is 7 %. Antecedent the probable avalanche triggering factors are:-

a. Freezing and thawing effects in the already jointed slopes might play pivotal role in triggering the rock failure, resulting the rock and ice avalanche.
b. The rock in the upper reaches might fail due to low / medium seismic shocks in the glacial area.
c. Lightening and cloud burst might trigger a slope failure for inducing the glacial avalanche.

The degree of risk because of glacial hazard in the vicinity amounts to certain actions by the decision makers which are based on quantitative risk assessment based on parameters e.g, location, elevation, slope, aspect, retreat and geomorphology of a particular area. The probable assessment of glacial areas dictates where there is a high probability of avalanche trigger / glacial hazard occurrence at places.

Settlement	Size	Degree of Risk (%)	Qualitative Degree of Risk	Remarks	Probability
ABC	Unit	80-100	Dangerous	Re Location	Very High
XYZ	Unit	60-80	Very High	Continuation at High Risk	High
123	Unit	40-60	High	Continuation at Moderate Risk	Medium

Table 4.4: Probability of avalanche trigger / glacial hazard occurrence.

5 CONCLUSION

The research area is comprised of two river basins, the Shayok and Shigar. The study of glaciers in these basins includes three important glaciers of northern areas of the Pakistan and their depletion estimation are carried out using remote sensing data and the topographic maps. For glacial hazard assessment of glaciers, the methodology adopted is followed to achieve the subject results.

53. CONCLUSION

a. The major glaciated sub basins of Indus River in HKH region of Pakistan are Shayok and Shigar. Most of the snow and ice reserves are concentrated in the mountain ranges lying in these basins which contain the glaciated part in northern Pakistan. The total ice reserve estimated in these basins is about 2,738 km^3 with contribution, Shayok (32%) and Shigar (21%). These ice reserves are subjected to manifest of global warming which is causing their decay, posing the glacial hazard to the settlements in the vicinity.
b. The total glaciated area in northern areas is about 15,041 km^2 which is 11.7% of the total area. The volumetric decrease of Baltoro, Biafo and Siachen glaciers is calculated as 7 % with an increase of 1.78^{0}C average temperature rise during the decade of 1990-2000. The aspect, slope, loc, elevation and geomorphology are the major factors for volumetric decrease / depletion of the glaciers.
c. There are several impacts of glaciers volumetric decrease / depletion subject to global warming, which need monitoring and early warning systems to protect infrastructure against the destructive forces of avalanches and outburst floods.
d. The settlement under threat of glacial mass movement and debris flow as located on the margins of an alluvial fan making the probability of occurrences very high.
e. The locations under threat of glacial hazard remain susceptible to land sliding and debris flow, for which necessary engineering remedial measures like retaining walls, gabions etc. will have to be put in place.

RECOMMENDATIONS

The integration of visual and digital image analysis with GIS has provided useful utilization for the research of glacial hazard. Based on conclusions of the research following is proffered:-

a. Settlement under high risk of glacial hazard be re-located at appropriate place and settlement under low risk of glacial hazard be continuously monitored with respect to debris flow.
b. For cont monitoring, Pakistan Met Dept (PMD) should establish AWS (Auto Weather Sta) at desired locs i.e, Goma, Dansam, Paiju, Burzil and Deosai to gauge / monitor the morphology of ice / snow cover and glaciers mass balance.
c. The seismic activities should be closely watched and in case of any such activity, the situation on glaciers should be monitored aerially.
d. The dangerous moraine dams, especially near the headwaters and settlements, needs to be monitored regularly, which are there as a consequence of volumetric decrease / depletion of these glaciers.
e. In the HKH region, inter-country flood warning systems should be established by devising a mechanism for sharing the costs and benefits of flash flooding mitigation works.

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 Command Northern Authority
FPSP	Flood Protection Sector Project
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 Research Commission
WAPDA	Water and Power Development Authority
WECS	Water and Energy Commission Secretariat
XS	Multispectral Mode Sensor System

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