Identification of Glacial Lakes, and Risk Assessment of Glacial Lake Outburst Floods (GLOF) In Astore Basin

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1. flood forecasting
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بِسۡمِ ٱللَّهِ ٱلرَّحۡمَٰنِ ٱلرَّحِيمِ

In the Name of Allāh, the Most Gracious, the Most Merciful

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FINAL APPROVAL

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DEDICATION

There are number of Pakistanis who are serving in such glaciated regions day in and day out, braving the weather so that we don't have to. I dedicate my research to all those who are serving in Siachen glacier and who have served before, specially the Martyrs of Gayari sector. This nation will remain a land of free only, so long as it is the home of braves. Thank you for all valour, bravery and sacrifices you made for us.

CONTENTS

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Maria Aslam

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LIST OF ABBREVIATIONS

Acronym	Abbreviation
HKH	Himalayan Karakorum Hindukush
GB	Gilgit Baltistan
GIS	Geographical information system
RS	Remote Sensing
NDVI	Normalized difference vegetation index
NDWI	Normalize difference water index
LULC	Land use land cover
GLOF	Glacial lake outburst flood
HECRAS	Hydrological engineering center river System
TIN	Triangular irregular network
DEM	Digital elevation model
STRM	Shuttel Redar topographic mission
PMD	Pakistan Meteorological Department
E	Erosion Lake
V	Valley type
L	Lateral Moraine
M	Moraine
B	Blocked
C	Crique type
S	Supra glacial
ICIMOD	International center for integrated mountain development
Lat	Latitude
Lon	Longitude

ABSTRACT

Abstract

In the past few decades, global climate change has a significant impact on the high elevated mountainous areas. As a result of this Himalayan, Karakorum and Hindukush in Pakistan region is also facing the effect of climate change in the result of rapid glacier melting, melting of ice masses, avalanches, creation of new lakes and expansion of old one posing high risk of glacial lake outburst flood (GLOF) in downstream communities. With the onset of twenty first century both the intensity and frequency of natural hazard like flash floods and GLOF have increased many floods in HKH range. The present study identification of glacial lake and risk assessment of glacial lake outburst floods (GLOF) in Astore basin has been undertaken to update digital data base of glacial lakes in context of changing climate pattern. The main objective was the identification of glacial lakes and the further prioritizes them on the characteristics of their potential vulnerability for downstream community. Identification was done by using Landsat 8 images and further validated by Google Earth. Systematic remote sensing and GIS studies have revealed the formation of 65 new lakes in area. The research finding would provide base for the development of a monitoring , planning and prioritization of disaster mitigation efforts that could save many lives and property in downstream region.

INTRODUCTION

1. Introduction

Climate change is a universal situation as influencing masses of community throughout the world, altering their secured existence into a doubtful one. Factors indicating the climate change include transformed landscape, rise in sea level and temperature, greater possibilities of drought, flash floods and fire with disease expansion and economic fluctuations. Likewise, it has been evidently proved that the change in global climate is prime factor contributing towards the decrement of glaciers all over the world (ICIMOD, 2005). Documentaries of the New York Times depicted the phenomenon of climate change as ''An Inconvenient Truth'' which is alarming (Risbey, 2008).

Greatest victims of the changing climate are the developing countries of the world. Among them the most troubled nation is ours (Gaffar *et al.*, 2010). Apart from Polar Regions, most of the world's glacial areas lie in Hindukush, Himalaya and Karakorum regions. About 33,000 square kilometers of glacial ice is spread over the Himalayan range alone. Approximately 15000 glaciers are located in the Himalayan range and those are depositories of fresh water. The region is also feeding nine supreme river systems in Asia supporting to over 1.3 million people through their basins (Breathier *et al.*, 2007). The world's massive storehouses of ice and snow are glaciers of Himalayas, increasing at alarming rate causing enlargement of the glacial lakes and existence in fragile mountain ecosystem is becoming unfavorable. Intense weather conditions are extremely common and rigorous (ICIMOD, 2005). In Pakistan the glaciers are melting at a very rapid pace as a result of global climate change. Melting of glaciers enhance the formation of glacial lakes and trigger the phenomenon of moraine and ice dams at the snout of glaciers. Abrupt out-bursts or breaches are ultimate outcome of such uncertain dams (Chaudhry *et al.*, 2009)

The highest accumulation of plateaus and mountains of the world are in the Hindu Kush-Himalayan (HKH) region. It contains many diverse, but integrated plateaus and mountain ranges that range upto 3,500 km from the northwest of Pakistan and Afghanistan as Hindu Kush, to the east of China as Hengduan Mountains. This is surrounded by "roof of the world" from huge Tibetan Plateau and multiple mountain ranges starting from the High Pamir to the Tien Shan, Kun Lun Shan, and Qilian Shan, majorly contributing towards global climate change. Area experiences high altitudinal and topographic variation like the world highest mountains exceeding the height of 8,000 meters covered with snow debris are located in this region. The area is at the verge of experiencing verse impacts of climate change further lead to the glacial retreat and massive melting which triggers the formation of new potential vulnerable glacial lakes within the boundary of Hindu Kush range. The Hindu Kush Karakorum and Himalayan region land masses are much more important because they control global wind circulations. Along with air masses, it's interactions with Indian monsoon system is a significant source of supplying fresh water to the world's greatest rivers. About one third of the world's populations use these resources as essential nourishment for life survival. Effects of climate change are also faced by glaciers as they melting at unprecedented rate. Seventy percent of human needs for survival are satisfied by these river basins. The melting glaciers and anterior moraine give rise to these glacial lakes between them. Nearly all of the glacial lakes reside on the bottom side of the glaciers. Uncertain complex moraines dam these glacial lakes, and have a likelihood of outburst and have potential to cause catastrophic flash floods. This phenomenon of Formation of Glacial Lakes has potential to cause glacial lakes outburst in downstream communities specially residing near Himalayan Karakorum Hindu Kush ranges (ICIMOD, 2010).

Over the last hundred years especially after the end of little ice age earth temperature has been increased from 0.3° to 0.6° (ICIMOD, 2007). Abrupt changes in global mean temperature causes faster melting of glaciers ice resulting in formation of large number of glacial lakes. A water mass in a sufficient amount and expanding freely in all directions of a glacier , and arising from glacial events is known as Glacial lake (Anand, 2014).

The joint venture between Water Resources Research Institute (WRRI) of the Pakistan Agricultural Research Council (PARC) and ICIMOD designed an inventory of glacial lakes and glaciers in the Indus basin of Pakistan based on the data collected between 2002 and 2005. 5,218 glaciers with an area of 15,041 sq.km and 2,420 glacial lakes were investigated, 52 of which were considered dangerous. About half of the total course of the Indus River is fed by glacier melt and seasonal snowmelt of the Karakorum, Hindu Kush, and Himalayas (ICIMOD, 2010).

These glacial lakes have been listed broadly according to their type including moraine-dammed, ice- dammed, erosion and other lakes (ICIMOD 2011).

1.1 Moraine-dammed lakes: Due to thinning and retreat of glacier tongue, melt water gets accumulated in the depression between the glacier terminus and its end moraine and such lakes are termed as moraine-dammed lakes. Some lakes also accumulate between the lateral moraine and the valley side along the glacier marginal weak dam structure have high tendency of bursting of glacial lakes.

1.2 Ice-dammed lakes: lakes dammed by glacier ice are termed as Ice dammed lakes. Further these lakes are classified as;

- Supra-glacial lakes: Supra-glacial lakes generally exist on glacier surface that is entirely covered by a thick layer of debris. As supra-glacial lakes grow, the left glacier ice below them melts and thus moraine-dammed lakes are evolved. These lakes often merge with moraine-dammed lakes, or sometimes may develop into composite forms:
- Glacier ice dammed lakes: Lakes dammed by glacier ice without lateral moraine is termed as glacier ice dammed lakes.

1.3 Erosion lakes: Erosion lakes are glacial lakes that form due to past glacial erosion process and exist in depression of glacier retreat region. They exist as cirque glaciers or as glacial trough valley lakes. They exist for from hundreds or thousands of years.

1.4 Other glacial lakes: Glacier valley floors receive masses from rock falls, debris flows or landslides, damming local streams of glaciers. Such lakes are called as other glacial lakes (Anand 2014).

In Karakoram and Himalayan regions natural phenomenon of glacial lake outburst flood (GLOF) is very active and powerful. Frequent and sudden catastrophic outbursts are useful indicators for environmental scientists for sketching the reason of climatic change and glacial fluctuation (Rehman, 2014).

Many catastrophic events of recent decades in mountain ranges are believed to occur due to glacial retreat. These events not only promoting to the development of new glacial lakes, also raising the amount of water collected in the present lakes (Clauge and Evans 2000).

Glacier lakes can be contained by moraines, which can fail and cause floods called glacier lake outburst floods (GLOFs). These GLOFs will contain water and granular material such as soil and small rocks, and can flow for many kilometers at high speed. As such GLOFs represent a serious hazard risk to regions downstream from the lake. For example, the October 7, 1994 failure of the moraine at Lugge Lake in the Lunana region, Bhutan, caused a GLOF that killed more than 20 people (Pitman et al. 2013)

Glacial lake outburst floods are not a recent phenomenon but have long been known to occur in different parts across the globe. A glacial lake outburst event caused massive disaster to the city of Huaraz in Peru and as result lead to killing of 4,500 people. Saas Balen village was adversely hitted by moraine dammed lake in 1968 and 1970. 400,000 cubic meters of debris had been eroded out in the event of 1968 glacieal outburst. In past many glacial lake outbursts floods flooded the territory of Himalayan-Karakorum and Hindukush ranges but due to lack of innovative technologies and satellite images data they were not recorded. Climatologist and researchers have proved that the Seti khola valley is also invaded by glacial lake outburst event back in 450 years. Debris accumulation was up to 50 meters deep covering a wide area of the Pokhara valley in west of Nepal. Sudden dammed out breach may also lead to seismic activities like lake outburst event on Machhapuchare mountain. (Carson 1985). This is not only one event. The risk of these events are increasing by each passing day especially during the last half century, and because of freely available data sets the investigated record has greatly improved. Previous data revealed glacial lake eruption events in Ladakh Range in Jammu and Kashmir (Gergan et al. 2009). This catastrophic phenomenon can increase transboundary flow of water masses. This transboundary event requires the attention of international community to minimize the life and property loss. The prime instance of these transboundary events is the breach of Tibet AR (China) that went across the international borders of Bhutan and Nepal.

Karakoram Himalaya and neighboring ranges experiencing the addition of new glacial lakes. (Rehman, 2014). A joint venture by ICIMOD, UNEP, and APN between 1999 and 2003 recorded about 15,000 glaciers and 9000 glacial lakes in Bhutan, Nepal, Pakistan and selected basins of China and India (ICIMOD 2007). IPCC in 2007 reported that there will be an increase in temperature in Himalayan region between 1 to 6°C by 2100. As a result of this more glacial ice will melt and snow cover would decrease between 43 to 81 percent leaving behind many more glacial lakes in future. Burst or sudden discharge of large volume of water along with debris from these lakes causes glacial lake outburst flood (GLOF) in valley downstream causing massive damage to infrastructure, natural resources and human life. The degree for loss of life and damage to infrastructure due to GLOF varies depending on various factors such as the size and depth of the lake, the nature of the outburst, the geomorphology of the river valley and elements exposed to the flash flood (Anand 2014).

Outbursts from series of dams on the Upper Shyok between 1926 and 1932 caused destructive floods affecting more than 1,200 km of the Indus. These mountain ranges are mostly covered with alpine glacial ice and, therefore, are carved and crafted into typical glacial erosional and depositional morphologies. These lakes are usually confined to the upper catchments and become potential hazards, which makes them dangerous and threatening to the communities settled down- stream. If these lakes are not frequently monitored and assessed, they can stun the community with their sudden outflows. Monitoring of these remote lakes in the Karakoram ranges is becoming inevitable because the government of Pakistan is investing a huge amount of budget on hydroelectric power plants at different locations along major rivers. A single outburst of one of these lakes can cause a severe damage to the ongoing developmental activities in the Karakoram Himalayas. The intensity and impact of GLOFs depends on the volume of the lake, physical perimeters, condition of the dam, and the gradient of the downstream drainage system. In certain cases, GLOFs can be extremely hazardous and can release enormous amount of energy, which eventually becomes a disaster for the communities settled down- stream. Therefore, it becomes imperative to assess the risk in order to build safer downstream communities and increase their preparedness against GLOFs (Rehman, 2014).

One of the spectacular effects of recent atmospheric warming in the Himalayan region has been the creation of meltwater lakes on the lower sections of many glaciers. Climate change is likely to exacerbate further some of these natural hazards such as glacial lake outburst floods (GLOFs), which can cause major social and economic damage for large populations living in the Himalayan region. Thirty-five destructive outburst floods have been recorded for the Karakoram Range in the past 200 years.

Hazards associated with glaciers such as flash floods, GLOFs, snow avalanches, and glacier-induced debris flows are becoming more common and frequent in the Pakistani Himalayas, which is believed to be the cause of retreating glaciers in response to global warming (Rehman, 2014). Damage caused by the outbreak of glacial lakes in the HKH region is by no means the only threat from what can be generalized as 'flash floods'. Such phenomena are also caused by the temporary damming of river courses by avalanches, landslides, rock falls, and similar events that restrict the normal flow of a river, and by torrential monsoon downpours. The understanding arising from the study of GLOFs and their causes will have some relevance to the broader category of the rapid discharge of waters.

1.2 Problem Statement

This study involves acquisition of data on climatic parameters which contribute in glacial lake outburst flood in Astore Valley, and analysis of their outburst potential which poses significant threats to human life and infrastructure. Furthermore, it will identify the hazardous lakes which cause flash floods in the Astore Basin and affect the downstream communities.

1.3 Objectives

- This study aims at systematic detection and delineation of glacial lakes in Astore Valley and prioritizing them on the basis of outburst potential.
- Evaluating the risk assessment of glacier lake outburst floods potential in Astore basin based on climatic conditions.
- Hazard assessment of downstream area of selected community.

LITERATURE REVIEW

LITERATURE REVIEW

2.0 Literature Review

Mukhopadhyay et al.,(2015) worked on snow and glacier melt of analyzing Upper Indus basin in the context of changing climatic conditions. To quantify base flow, seasonal snowmelt, and glacial melt components in river flows within upper Indus basin hydrograph method was used. Monthly average river discharge values recorded as primary data set at gauging stations as daily flows covering the period 1962–2010. The results indicates that hydrograph method is suitable in order to measure mass balance irrespective of uncertainty.

Zhang *et al.*,(2015) focused on glacial lakes inventory in the Third Pole region and their changes in response in context of climate change and global warming by using landsat data of 2010. They basically identified the area changes in three years. According to their findings 4602, 4981, 5701 glacier lakes and there number can be increased due to global warming and increase temperature trends leads to retreat of glacier mass balance patterns. Particular there is a considerable increase in glacial lakes area as compared to non-glacial lakes. Lakes which are at snout of glaciers are relatively increasing in size. Lakes specially at mountains and glaciers are experiencing more significant area changes. Results reveled that water cervaces and dammed area lead to expansion of glacial lakes.

Vilmek *et al* .,(2015) worked on the geomorphologic impacts of glacier lake outburst flood from lake No. 513 (Peru). This study basically highlight the GLOF event which have occurred in Peru in 2010.Landuse area and other land form feature are characterized by field investigation. Pervious GLOF events were witnessed by using remote sensing technique. In order to compare field data, potential for GLOF event and risk assessment HECRAS hydrological model was used.

Khanal *et al.*,(2014) Carried out a research on the strategies and procedures for glacier lake outburst flood risk assessment, with example from Nepal and trans boundary area. their findings reveled that Nepal is at high risk of glacier lake out bursts floods (GLOFs) the main reason behind that is climate change. The risk of GLOF is heightened due to rapid melting that further trigger the formation of new glacial lakes and expansion of the recent one. First step was to identify and prioritize critical glacial lakes and second was field investigation of critical lakes. Final approach was to find the outburst potential of moraine dam failure and mapping the inundated flood area. As a result four glacial lakes were identified that can cause serious damage to the downstream community.

Shresta and Nakagawa., (2014) conducted research on evaluation of outburst floods from the Tsho Ropla glacial lake in Nepal. The distinctiveness of possible outburst floods is mainly due to two types of moraine dam failure from the Tsho Rolpa glacial lake. one was due to seepage flow. Water overtopping were analyzed by using three numerical models (1) the flow and bed-surface erosion model, (2) the seepage model and (3) the slope stability model. Through numericals models of the flow Flood inundation areas were also identified. Moraine dam failure and geographical information system tools were used in order to map hazard . Field investigation and numerical modeling was carried out in order to save community from potential effects of GLOF hazard.

Worni et al., (2014) worked on the coupling glacier lake impact, dam breech and flood processes. In this study surrounding conditions , cascades and physical process are also focused which enhance or trigger the GLOF event. Mainly focused on the factors like rock and land sliding and amount of ice and debris over the surface of glaciers. Finally focused on the diverse scientific researches across the world that collectively highlighted the potential and limitations of current GLOF modeling. They concluded that process chain model need to be strengthened for proper computation of numerical models.

Fujita, et al., (2013) Focused on the proper monitoring of potentially dangerous glacial lake which cause the GLOF event in Himalayan region. The research focus on the selection of suitable lake indexes in order to place it in potentially dangerous lake category. They introduced a single index based on stored water dam condition and DEM of the area.

Vilimek *et al* .,(2013) explored the data base of outburst floods (GloFs –IPL ,Project number 179). They basically worked on the online data base including GIOF events across the globe specially after little ice age period. There study is basically based on the scientific literature, published and unpublished report and regional data bases, as well as collaboration with international organization and national services. This information is helpful for hazard assessment, mitigation and consequently risk management.

Zhang .,(2013) explored the characteristics of runoff inflow in to lake Gojal in ungauged, highly glacierized upper Hunza river basin, Pakistan. They worked on the lake outburst that was dammed by the land slide. Two hydrological models were used along with sparsely observed data. STRM and ASTER DAM were used in order to analyze area volume relationship. Results include the estimation of hydrological parameters.

Wang *et al.,* (2012) worked on the evolution of evaluation of ASTER,GDEM, and SRTM and their suitability in hydraulic modeling of glacier lake outburst flood in southeast Tibet .Hec-Ras hydrological model was used in order to predict risk assessment , Peak flow ,flood inundation, extent and depth. Modelling results shows that, in the absence of high-precision DEM data, ASTER ,GDEM or SRTM DEM can be relied on for simulating extreme GLOFs in southeast Tibet.

Worni *et al* ., (2012) .Their study highlighted the failure of the terminal moraine in Ventisquero Negro, Argentina because of the glacial lake outburst flood event .A recent glacier lake outburst, due to in May 2009.BASEMENT two dimensional numerical model was used in order to investigate end moraine and lake drainage. Field work was carried out in order to gather data on breach,lake geometry, and wetted cross sections. Results indicated that by a rising lake level due to heavy precipitation, leads to the moraine failure. which led to dam erosion and finally to dam failure because of GLOF event.

Arshad, et al.,(2011) analyze remote sensing data of Land-sat ETM+ was utilized for the identification of glacial lakes susceptible to posing glacial lake outburst flood in

Karakorum and effect downstream community out of, 887 glacial lakes 16 lakes are characterized as actually dangerous in terms of Glacial Lake Outburst Floods (GLOF).

Rasul, et al., (2010) carried out an investigative study to sketch the behavior of glaciers in Himalayas, Karakoram and Hindukush. According to their glaciers are melting at unprecedented rate due to climate change and global warming. As a result event of glacier lake outburst floods are also increasing in number result in massive loss to the property and life of community.

Rasul, et al., (2008) analyze the trend of glacier melting due to global climate change scenario and global warming According to his study anthropogenic and natural activities are leading to glacier melting and sever climate change. Remote sensing data along with hydrological and meteorological parameters was used. They future reviled that high temperatures are also disturbing the glacier mass balance.Extreme temperatures would further exaggerate the ice depletion and mass balance

Quincey *et al* .,(2007) worked on Data sets of ERS-1, ERS-2,SAR and SPOT-5 imagery was used. The Joint approach was established for analyzing glacier surface gradient and glacier velocities. It is very useful predicative tool for the assessment of glaciers which are vulnerable to lake development. Results indicated that majority of glaciers are flowing at rate of few tens Centimeter every year resulting in increase the risks of GLOF event.

Carrivick .,(2006) highlighted the method include calculation of high magnitude hydrological parameters drainage lines and drainage patterns of network. Study further highlighted the potential for further researches because in current scenario wide range of DEM data is available along with advance remotes sensing techniques in order to identify the outburst flood resources.

Watson *et al.*, (2005) worked on coupled models contrast of remote sensing and a GIS-based technique was presented. They basically highlighted and quantified the differences among the methodologies while using Landsat data sets along with DEM products. Results concealed DEM uncertainties and numerous flood parameters are analyzed by using model products and on the prediction of socio-economic impacts.

MC-LCP(Monte Carlo Least Cost Path) was used in order to evaluate the socio-economic risks.

Kaab, *et al* ., (2005) investigate the air- and spaceborne remote sensing methods suitable for glacier and permafrost hazard assessment and disaster management. A number of image classification and change detection techniques support high-mountain hazard studies. Digital terrain models (DTMs), derived from optical stereo data, synthetic aperture radar or laser scanning, was used is one of the most important data sets for investigating high-mountain processes. Fusion of satellite stereo-derived DTMs with the DTM from the Shuttle Radar Topography Mission (SRTM) is was used to combine the advantages of both technologies.

Huggel, et al .,(2003) Debris flows triggered by glacier lake outbursts have repeatedly caused disasters in various high-mountain regions of the world. This study focused a modeling approach which takes into account the current evolution of the glacial environment and satisfies a robust first-order assessment of hazards from glacier-lake outbursts. Two topography-based GIS-models simulating debris flows related to outbursts from glacier lakes are presented and applied for two lake outburst events in the southern Swiss Alps.

Cronwell *et al*., (2003) carried out research on drainage, sediment transport, and denudation rates on the Nanga parbat Himalaya, Pakistan. In order to determine the stream flow condition of this area is a challenging issue due to its geomorphologic conditions. As there is no gage station in that specific basin, So field survey were carried out in order to collect cross sectional profiles of selected reaches. Collected data was incorporated in a software (winXSPRO) that help in the characterization of high altitude, steep mountain stream condition.

Clague *et al*.,(2000) conducted a research on the Catastrophic drainage of moraine dammed lake in British Columbia. The core intention was to document how moraine dam form and fail, and to provide insights on failure processes and hazards. Most moraine-dammed lakes have formed during the last 200 yr as glaciers retreated from their Little Ice Age maximum positions. The moraines are usually steep sided and consist of coarse, poorly sorted, cohesion less sediment. Outburst floods from moraine-dammed lakes typically are many times larger than snowmelt and rainfall foods in the same basins. Climatic warming may cause some moraine dams to fail, both by melting ice cores and by increasing the amount of water flowing over the moraines.

Richardson *et al.*, (2000) worked on the glacial hazards in the Himalayas. Glaciers vulnerability coupled with a particularly related river catchment in central Buthan was examined. All the glaciers across the country were also analyzed. This was done by using SPOT imagery from 1989-1990. Over 300 glaciers were examined in detail from the satellite images and geo-hazard assessments were undertaken on 154 glaciers. As glaciers recede in response to climatic warming, the number and volume of potentially hazardous moraine-dammed lakes in the Himalayas is increasing. These lakes extend behind unstable ice-cored moraines, and have the potential to burst catastrophically, producing devastating Glacial Lake Outburst Floods (GLOFs). Regardless of the scale of the risk, it is possible to assess and mitigate hazardous lakes successfully.

MATERIALS AND METHODS

3. Materials and Methods

This section outlines all the standard procedures to meet aims and objective of studies.

3.1 Study area description

Astore is a mesmerizing and beautiful valley of Gilgit-Baltistan located in Northern part of Pakistan between 34.8°-35.8° N latitude and 74.4°-75.2° E longitude. Astore processes altitudinal and topographical variation. The lands are deeply cut by rushing hill torrents and rugged topography forming V-shaped valleys. Alpine meadows are permanent snow covered mountains at lower valley parts. Bunji including up to Doain are arid, dry and warm and upper part of the valley i.e., Deosai, Domail, Kalapani, Rupal and Rama etc. are cold and some of the most beautiful places in Pakistan. The valley covers an area of 7222 km2 (Ali *et al.*, 1995). It is bounded by Baltistan, in south East, Gilgit East North, Chillas and Azad Kashmir in West. The valley extends over the major part of the Western Himalayas.The Himalayas are one of the most representative mountain ranges which have vast alpine vegetation and great varieties of plants. (Noor *et al* .,2013)

Astore River drains the snow and glacier covered mountains of Laddakh - Deosai and the High Himalayan range east of the Nanga Parbat Mountain. The elevation of this basin ranges from 2,104 to 5,993m. Astore River rises from a glacier on the north-facing slopes of the great Himalayan range near the Burzil Pass in the Laddakh region of Jammu and Kashmir. It flows towards northwesterly direction and joins the Indus River soon after it emerges from the main Himalayan gorge a little downstream of Bunji.

There are many habitats, arid desert plains, temperate conifer forests, sub alpine bushes to alpine meadows and permanent snow covered mountains. The average minimum temperature in winter is 2.8°C and the maximum temperature in summer is 20.8°C. The summer season is very short lasting from May to August. Relative humidity is much higher in the morning than the evening. The mean monthly precipitation is 33.9mm to 750mm. In lower altitude of the area it falls as rain and upper zones mostly as snow. (Noor *et al.*, 2013).

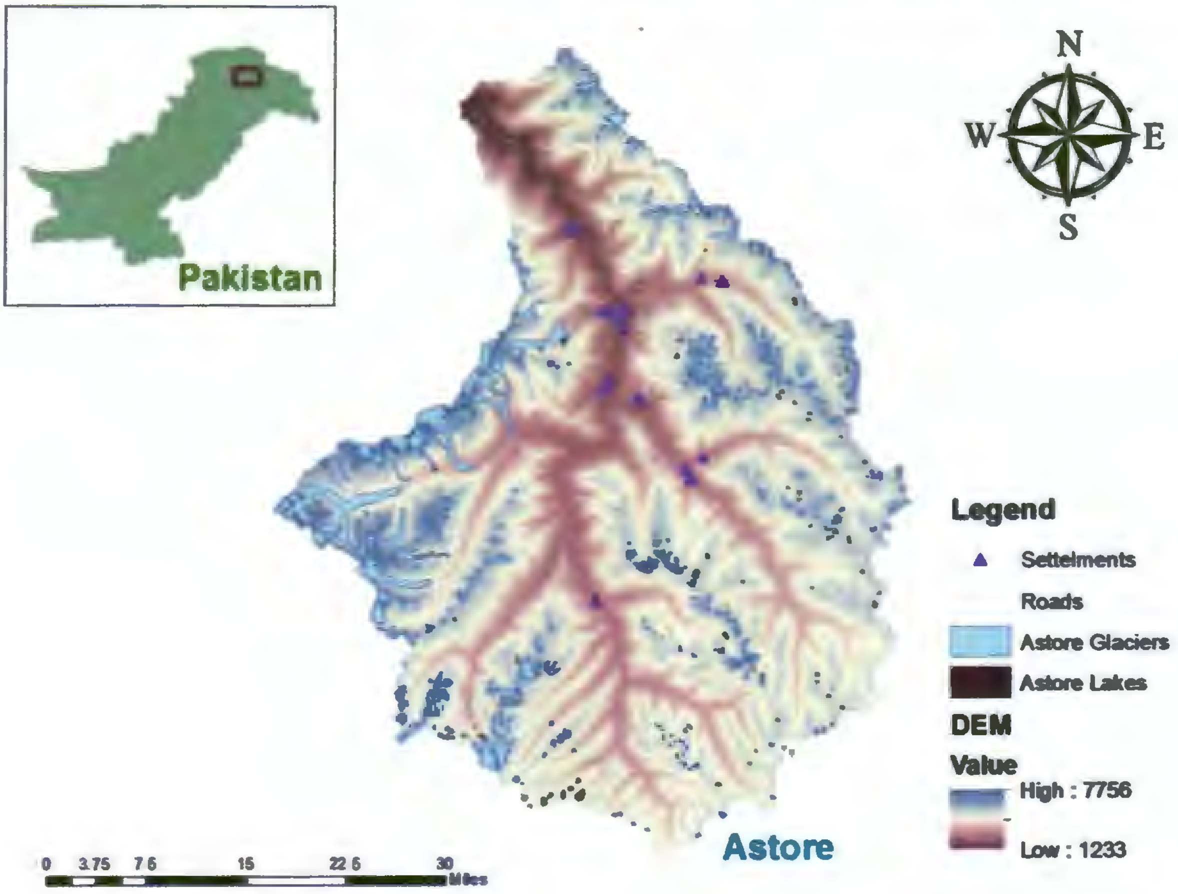

Figure 3.1 Study area Map

3.2 Data Sets

In the present study landsat-8 image was used for the identification of glacial lakes. It was supported by limited ground truth verification. Land –sat of 7 plus band with 149/35 and 149/36 path/row were selected Images were acquired from http://www.usgs.gov

Annual temperature and rainfall data records was acquired from Pakistan Meteorological Department (PMD) for the year 1990-2015. Settlements mapping was computed in GIS and validated Google Earth. Roads were digitized in order to determine their distance from lakes. Physical condition of every lake and its surrounding area was analyzed by using satellite images and Google Earth tool. Slope and aspect were extracted from DEM (Digital Elevation Model). STRM (Shuttle Radar Topography Mission) DEM of 30 meter resolution was used to drive the basin information.

3.3 Identification and classification of Glacial lakes

Glacial lakes were identified by using Google Earth. After Identification Lake boundaries were digitized, the segments were checked and the glacial lakes were numbered. After digitization longitude, latitude and elevation are designated for the approximate center of glacial lake. Type of lake was identified either they were erosion, valley, trough, crique, blocked or moraine dammed to further classify them. Identified lakes were further classified as one of eight cardinal drainage directions viz (N, NE, E, SE, S, SW, W and NW). Glacier later poses /drainage was placed in two categories C (Clear type), D (Debris type). Area was measured in meter square .

Layer stacking of the images was processed in ERDAS software. Image mosaicing was done by using image mosaic tool. Lakes were further featured by using different variables and indexes Such as Normalized Difference Vegetation index (NDVI) and NDWI (Normalized Difference water Index).Arc- hydro tool in GIS was used in order to feature drainage point, catchment and drainage lines. Criteria analysis was done in order to examine lakes and potentially most dangerous lake.

3.4 Criteria Analysis for GLOF

Criteria analysis for potentially vulnerable lakes was developed based on type identification, activity of supra glacial lake, condition of dam and associated mother glacier, physical condition of surrounding area, evidence of deep seepage, distance from roads, distance from settlements, rainfall and temperature.

Based on these factors two categories viz., the risk prone lakes and the most dangerous lake with the potential of outburst flood were formed.

3.5 HECRAS Processing for GLOF Risk Assessment

The outburst flood potential of most dangerous lake was done by using hydrological climate model HECRAS 4.1.0 version. It is basically one dimensional mathematical model for hydraulic calculations developed by US – Army crop of Engineers. The model was used for the hydraulic calculations and steady and un steady flow of river. Hec-GeoRAS input files were prepared in GIS. After Ras layer preparation data was imported in to HECRAS for further computing and processing.

The specific technique adopted for assessment of outbursts flood of potentially dangerous lake is as follow

1- TIN was prepared through Arc view in ARC GIS.
2- After pre-processing HEC-GeoRAS export files are incorporated.
3- Simulation of HEC-RAS model was done in order to calculate water surface profile.
4- Floodplain. Mapping and cross sections were processed in HEC-RAS.
5- Flood inundation and risk assessment in order to save downstream communities.

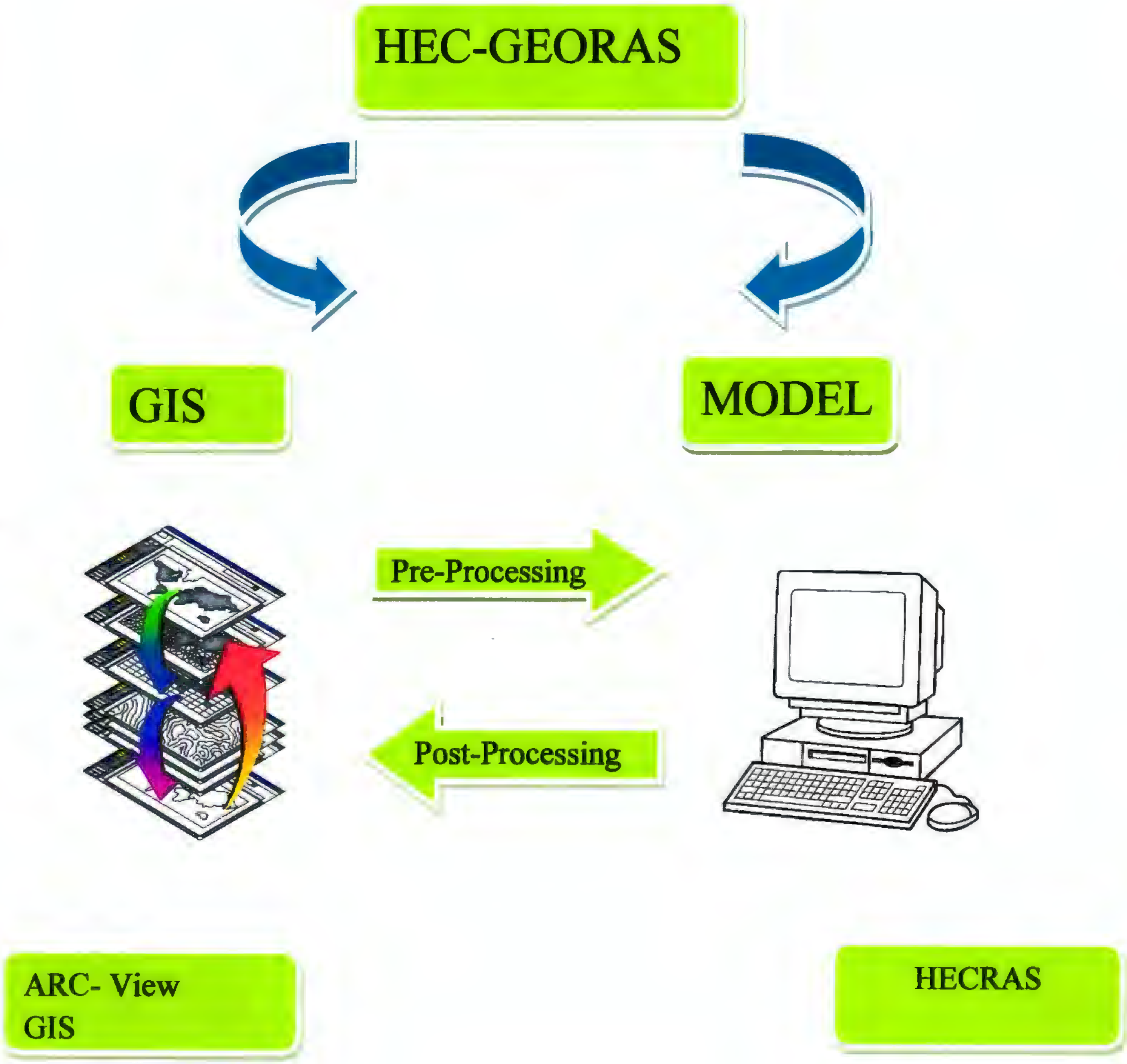

Fig 3.2: Interface method of GIS- linkage by HEC-GEORAS

Hec-GeoRas extension in Arc GIS was used for the preparation of geographical data and further processing. TIN file was generated for 30 meter resolution image. Main stream was digitize by using the digitization tool of Arc-GIS over tin file. Total length of tributary up to Astore river is 35km. Afterward flow paths and banks were digitized with high accuracy. There is no made infrastructure like bridge and obstruction points in the area. The cross sectional geometries were developed based on the available DEM (Digital Elevation Model) and TIN model of the area. Total 104 cross sections were developed on 35 km long river. Cross sections were developed manually by maintaining constant distance. Mannings roughness coefficient (n-values) was allocated in accordance with available literature. Total 5 classes were selected to analyze the land cover. Satellite image of late summers of year 2014 was used for the land use. Classification was done Ecognition software. It is basically original object based image analysis. Classification results were afterward merge in Arc-GIS.

Mannings	Values
Rocks	0.55
Vegetation	0.035
Glaciers/Snow cover	0.04
Water body	0.05
Unclassified	0.02

Table1: Table showing Mannings values (Source: Modeling of Bagrot and Bindogol river basins in Gilgit and Chitral Valley)

The preprocessed Hec-GeoRas layer was then exported in to Hecras model to finalize the hydraulics. Cross sections validation was done by Google Earth. Steady flow was generated on three different profiles in order to map flood inundation properly. The output generated by model and hydraulic data prepared was then imported in to Arc GIS so that two and three dimensional flood plain visualization .Three flood waves were generated and were classified on the basis of high, moderate and low flood. The final output was crosschecked by Google Earth.

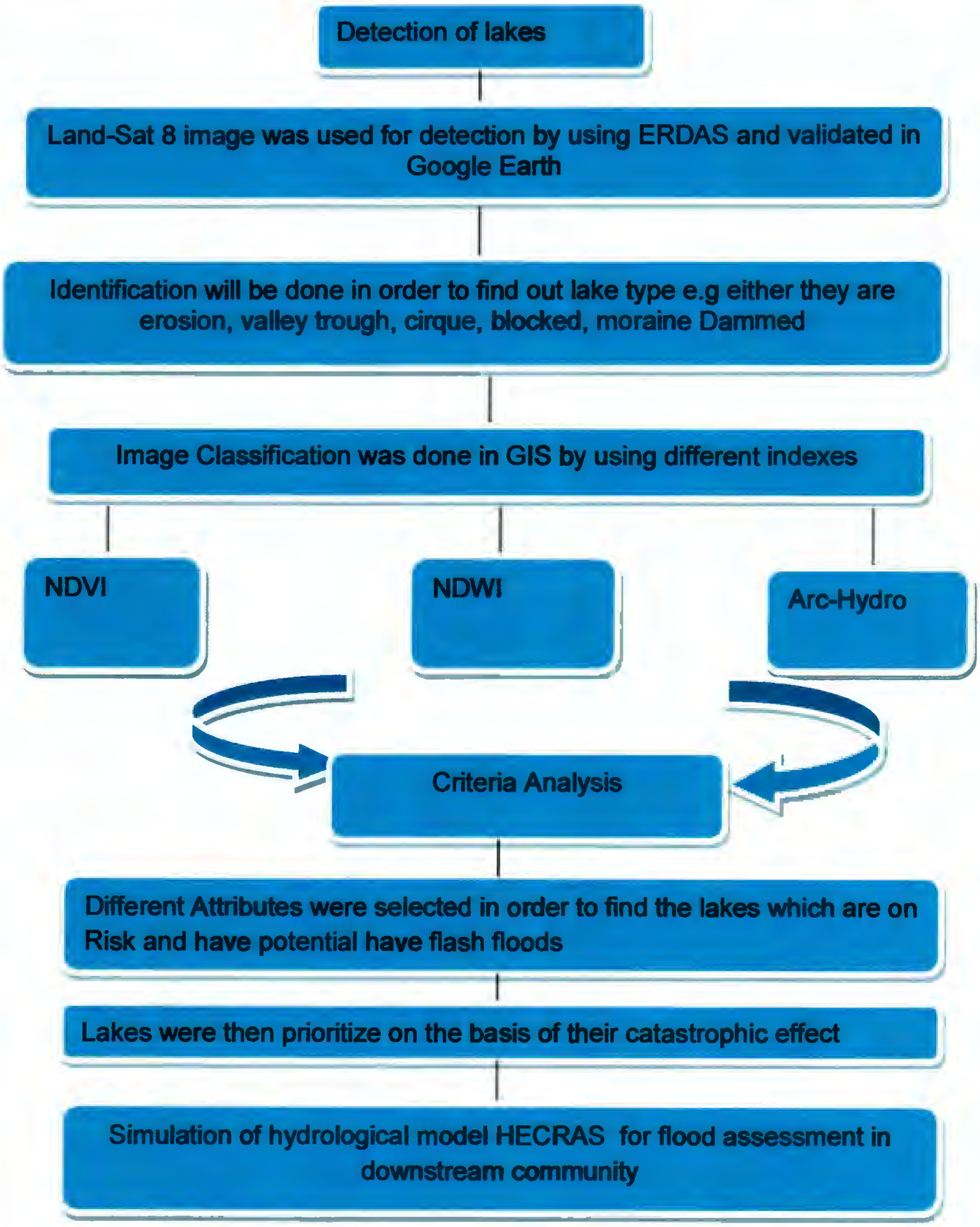

Figure 3.3 Flowchart explaining over all Methodology

RESULTS AND DISCUSSION

4 Results and Discussion

Main objective of the research was the identification of glacial lakes in Astore basin and prioritize them on the basis of their risk assessment in order to save downstream community from the catastrophic effects of flash floods. There were 196 glacial lakes identified by NARC in Astore basin in 2013 in which 6 lakes were declared potentially at risk to create flashflood in nearby areas. The data record of those lakes date back to 2010.,(APN 2013).

4.1 Identification of Glacial Lakes

Current study aims at identification of glacial lakes in Astore Basin. Glacial lake identification and assessment is important for monitoring of GlOF hazard and also in the perspective of resource management. A digital database plays a vital role in monitoring of glacial lakes and to identify the potentially dangerous lake. For spatial data input and attributes GIS is the most appropriate and recommended tool. A glacial lake outbursts flood is created when water is released catastrophically by glacier due to moraine failure. Glacial lake outburst flood is characterized by immediate outpour of massive quantity of sediments laden down from glacial lake that comes down to the river channel in downstream region in the form of flood wave (Pakistan GlOF project 2015). A local community which resides near Himalayan region is more vulnerable due to increased frequency of these hazards.

When compared with findings of NARC 2013, increased number of glacial lakes was observed in year 2015 attributed to global changing climatic pattern, global warming and changing annual precipitation cycle.,(Arshad *et al* 2011). The parameters and criteria adopted for identification of lakes were same by using satellite images and GIS facilities. The criteria used for identification were

- Lake type identification either it is erosion, moraine, blocked valley, criqure or supra-glacial lake.
- Activities of supra glacial lake.
- Dam condition
- Condition of associated mother glacier.
- Physical condition of the surrounding area.
- Evidence of strong seepage.
- Distance from road.

- Distance from settlement.
- Slope.
- Temperature.
- Precipitation

In addition to 196 identified lakes by NARC , 65 new lakes were identified in the present study in Astore basin. Majority of glacial lakes are 'Erosion' (i.e.40) followed by Moraine (i.e.13), and Valley (i.e. 12). Lakes identification number was given according to NARC, furthermore latitude, longitude, elevation was assigned accordingly. Area was also calculated in (m^2). Detail of newly identified glacial lakes till 2015 are presented together with their information below

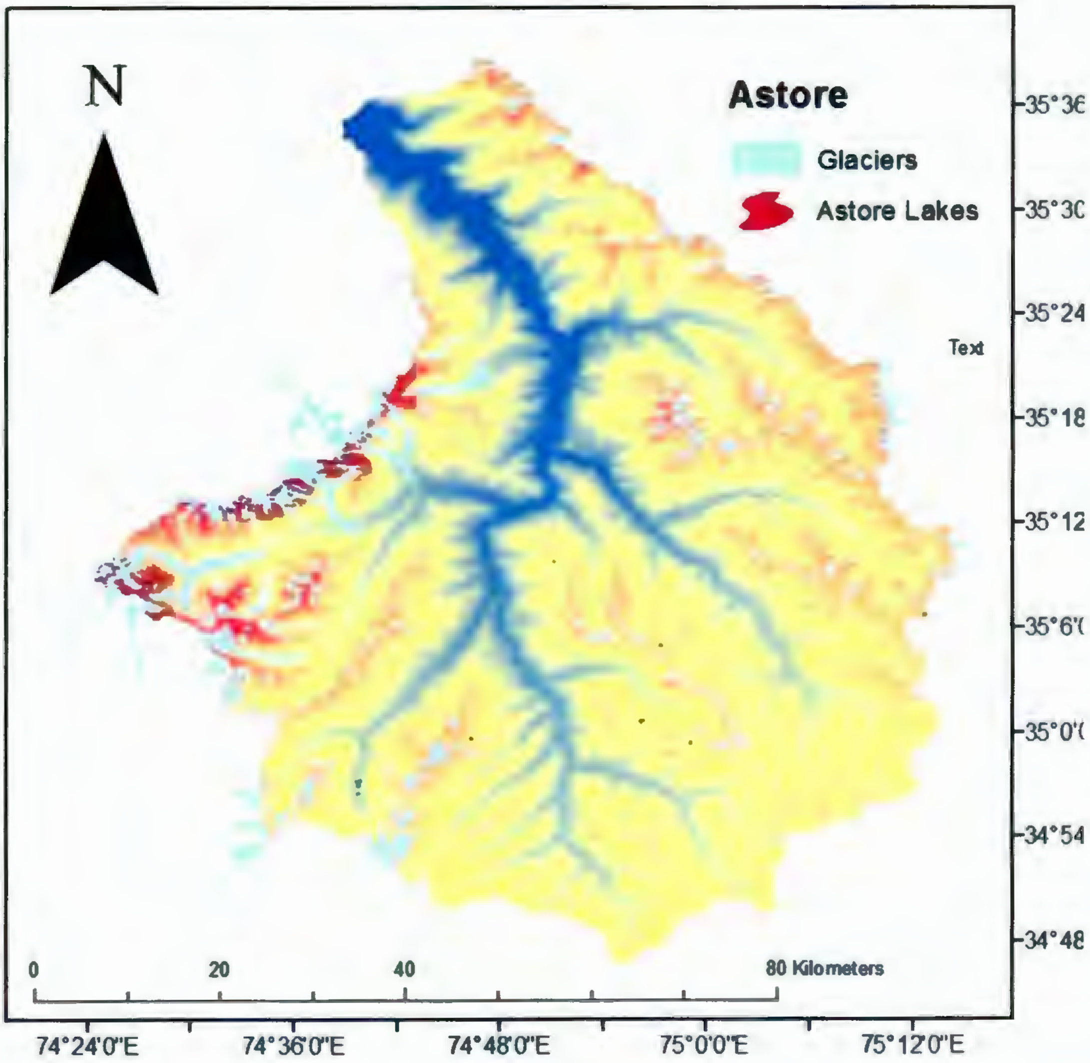

Figure 4. 1: New identified lakes in Astore Basin

Lake Number and type	Longitude E	Latitude N	Area (m^2)	Elevation
Ast_gl_1 (C)	75°9	35°20	24171	4634
Ast_gl_2 (E)	75°03	35°18	16795	4968
Ast_gl_3(E)	75°10	35°18	6695	4915
Ast_gl_4 (E)	75°10	35°18	4085	4914
Ast_gl_5 (E)	75°10	35°17	22752	4914
Ast_gl_6 (E)	75°94	35°17	7887	4749
Ast_gl_7 (E)	75°94	35°16	6582	4656
Ast_gl_ 8 (E)	75°95	35°16	30324	4774
Ast_gl_9 (E)	75°83	35°16	7969	4305
Ast_gl_10(E)	75°93	35°6	15773	4496
Ast_gl_11(E)	75°93	35°6N	17817	4497
Ast_gl_12(E)	75°93	35°6	48742	4373
Ast_gl_13 (V)	75°12	35°6	13220	4663
Ast_gl_14(E)	75°12	35°6	7523	4618
Ast_gl_15(E)	75°12	35°7	71334	4610
Ast_gl_16(E)	75°12	35°7	44440	4616
Ast_gl_1(E)	75°12	35°7	11365	4632
Ast_gl_18(E)	74°58	35°4	37732	4465
Ast_gl_19(C)	74°57	35°4	8170	4354
Ast_gl_20(E)	74°56	35°4	23878	4525
Ast_gl_21 (E)	74°58	34°59	5320	4383
Ast_gl_22(E)	74°59	34°59	18392	4355
Ast_gl_23(V)	74°56	34°54	13674	4211
Ast_gl_24(M)	75°86	35°15	5770	4712
Ast_gl_25(V)	75°81	35°15	21220	4654
Ast_gl_26(E)	74°46	34°59	34384	4361
Ast_gl_27(E)	74°50	35°34	36685	4464
Ast_gl_28(E)	74°55	35°18	3341	4184
Ast_gl_29(E)	74°55	35°18	8465	4175
Ast_gl_30(M)	74°55	35°17	5982	4192
Ast_gl_31(M)	74°46	35°20	57558	3648
Ast_gl_32 (E)	75°35	35°9	10553	4572
Ast_gl_33 (E)	74°53	35°1	50101	4341
Ast_gl_34 (E)	74°53	35°1	50101	4341
Ast_gl_35 (E)	74°57	35°0	3745	4461
Ast_gl_36 (E)	74°39	34°56	13958	3291
Ast_gl_37(E)	74°51	35°9	5826	4096
Ast_gl_38(M)	74°40	34°59	5703	3260
Ast_gl_39(M)	74°40	34°58	12765	3245
Ast_gl_40(V)	74°40	34°58	31372	3258
Ast_gl_41 (M)	74°40	34°58	9174	3275
Ast_gl_42 (M)	74°40	34°58	10894	3281
Ast_gl_43(M)	74°39	34°57	47264	3298
Ast_gl_44(E)	74°39	34°57	5958	3292
Ast_gl_45(M)	74°39	34°57	28653	3291
Ast_gl_46(E)	74°39	34°57	13285	3292
Ast_gl_47 (M)	74°39	34°57	23604	3290
Ast_gl_48 (V)	74°39	34°57	23317	3288
Ast_gl_49 (E)	74°39	34°57	8808	3288
Ast_gl_50(M)	74°39	34°56	46979	3291
Ast_gl_51(E)	74°39	34°56	9552	3292
Ast_gl_52 (M)	74°39	34°57	61222	3293
Ast_gl_53(E)	74°39	34°57	25362	3295
Ast_gl_54(E)	74°56	35°0	12199	4111
Ast_gl_55(M)	74°58	34°59	8908	4374
Ast_gl_56 (M)	74°54	35°28	7190	4200
Ast_gl_57(E)	75°55	35°15	13447	4289
Ast_gl_58(M)	75°54	35°15	19235	4286
Ast_gl_59(E)	75°71	35°10	26079	4552
Ast_gl_60(E)	75°72	35°10	6863	4610
Ast_gl_61 (V)	75°61	35°9	3095	4576
Ast_gl_62 (E)	75°06	35°08	3440	4616
Ast_gl_63 (V)	75°12	35°07	5410	4614
Ast_gl_64 (V)	75°12	35°07	8733	4602
Ast_gl_65(M)	75°12	35°07	7190	4631

Table 4.1: Data base of new identified lakes in Astore basin

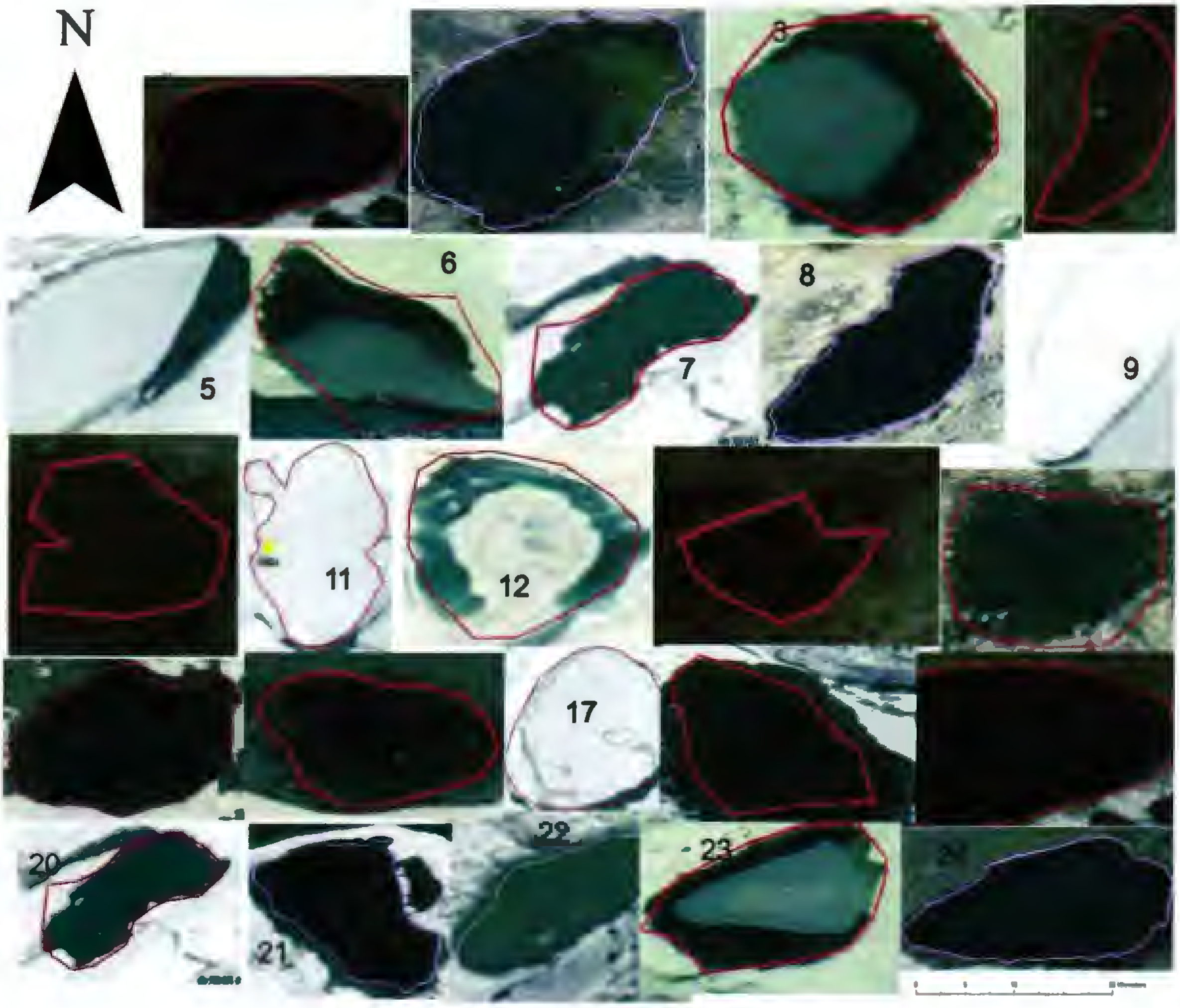

Figure 4.2 : New identified lakes in Astore basin

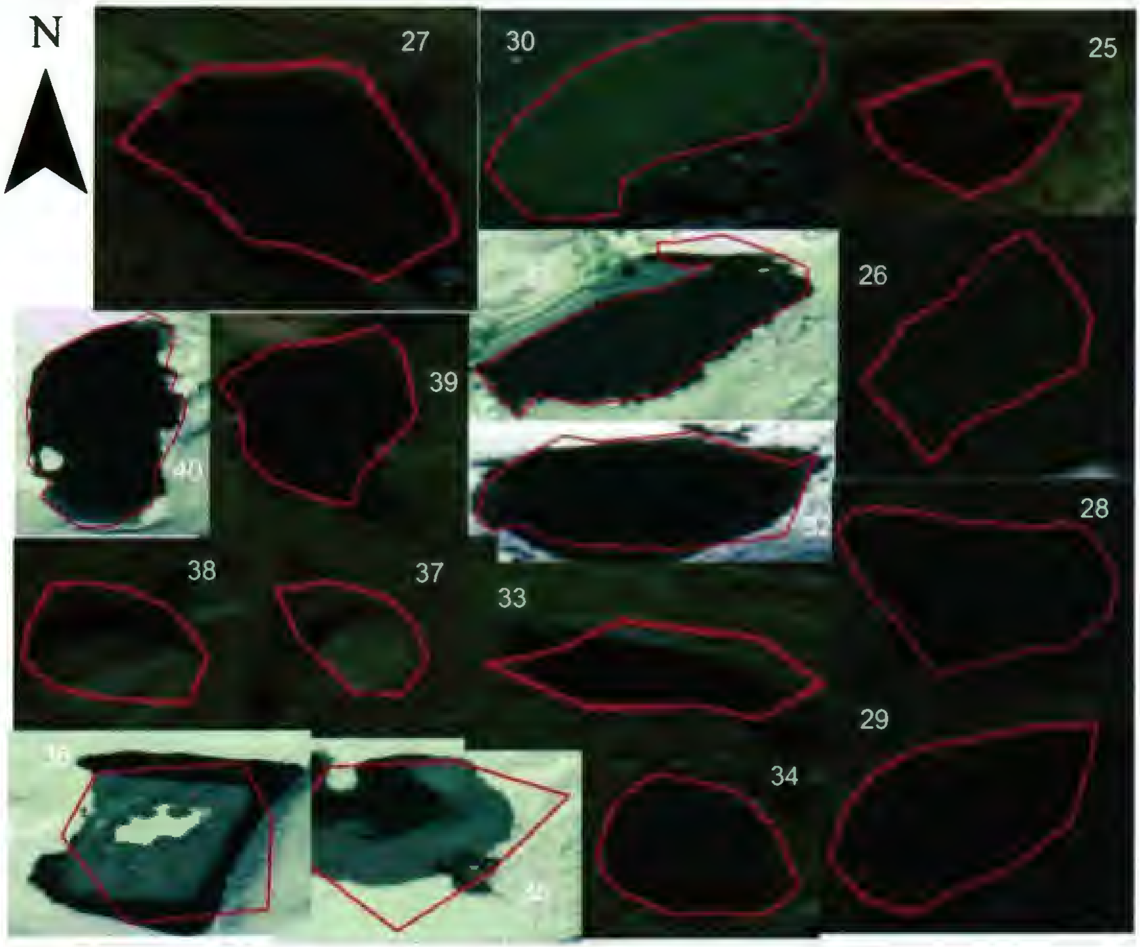

Figure 4.3: New identified lakes in Astore basin

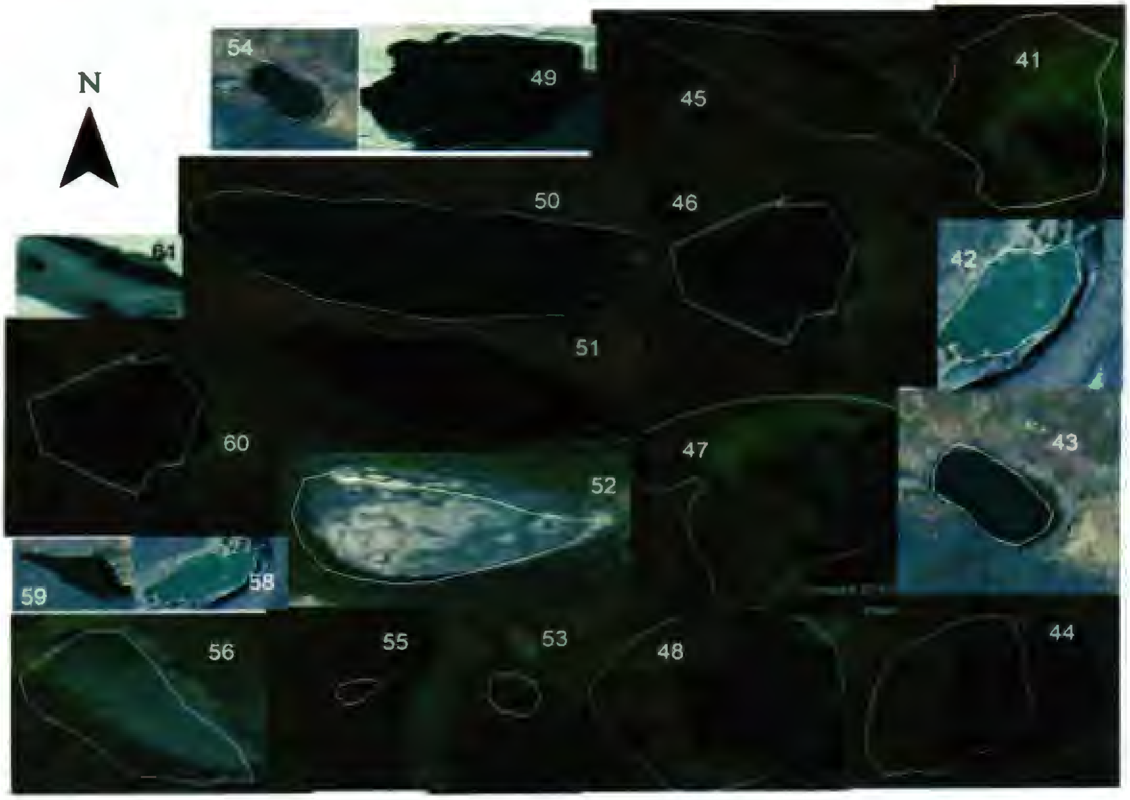

Figure 4.4: new identified lakes in Astore basin

4.2 Normalized Difference Water Index (NDWI)

It is a dimensionless product and varies between -1 to +1 depending upon the vegetation type and cover and on the leaf water content. High values of NDWI in blue correspond to high vegetation water content and to high vegetation cover. Low NDWI values correspond to low vegetation water content and low vegetation fraction cover.

$$NDWI = \frac{Green - Near\ Infrared}{Green + Near\ Infrared}$$

Highest value of NDWI is 0.4 and the lowest value is -0.4 .Mostly the area under the glacier cover depict high water content than rest of the area. The areas near Chich pass, Tashain glacier, ridge of Siachen , Rupal side of Nanga parbet, Mazinobase, Moshkin and Riat valley are areas where maximum water content lies. Areas which are under infrastructure, settlements, and agriculture field processes low NDWI values.

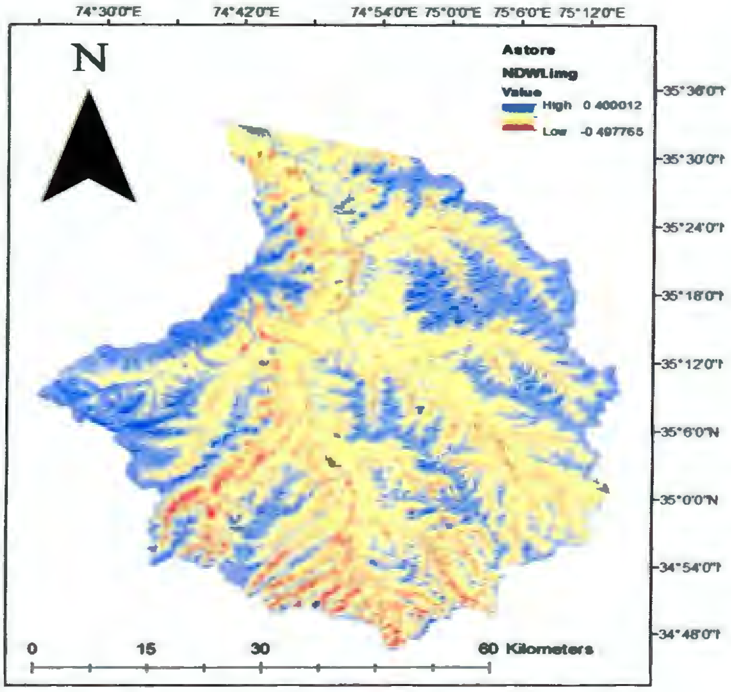

Figure 4.5: Normalize Difference Water Index of study area

4.3 Normalized Difference Vegetation Index (NDVI)

The Normalized Difference of vegetation index includes subtraction of the red reflectance values from the near infrared and divides it by the sum of both.

$$NDVI = \frac{Near\ Infrared - Red}{Near\ Infrared + Red}$$

The highest value of NDVI is 0.5 and lowest value is -0.3 .Mostly populated areas with high settlement ratio shows high NDVI values while glaciated region depict less NDVI values. Deosai, Burzail pass, Chillam, Chogham , Mir Malik Village , Naugam Khirim, mankail, Gorikot, Harchu, Guadai shows high NDVI values.

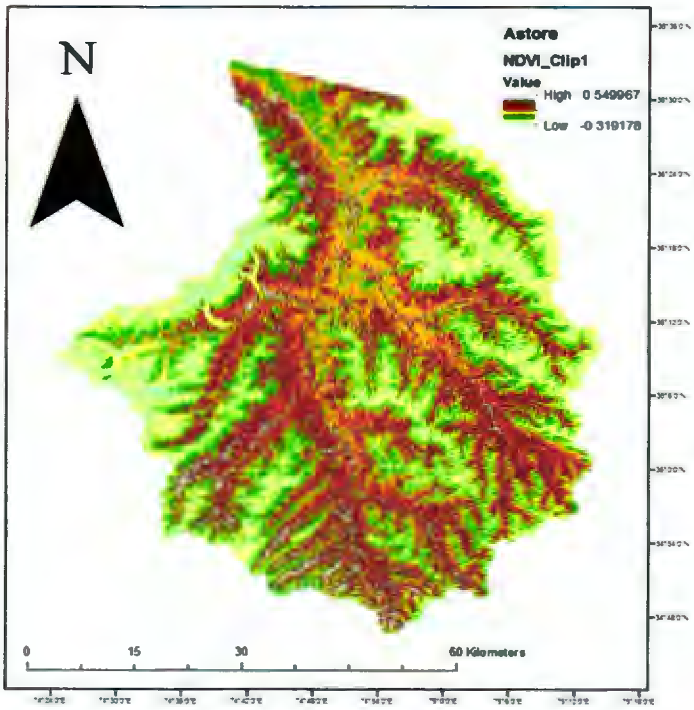

Figure 4.6 : Normalize Difference vegetation index of Astore

4.4 Arc-Hydro Model

Arc-Hydro tools were used in order to determine drainage line features of basin accurately and repeatedly in an automated fashion. Arc-hydro is basically a set of data models and tools that operates with in Arc-GIS to support geospatial and temporal data analysis. Delineation and characterization of watersheds in raster and vector formats, can be extracted by Arc-Hydro and further used to define and analyze hydro-geometric network of the area. Doain, catchment of Astore basin was extracted to determine land area that drain in to the hydro-network. Modeling of hydrological system involves exact determination of catchment boundaries. Drainage lines and drainage points were also extracted for accurate modeling.

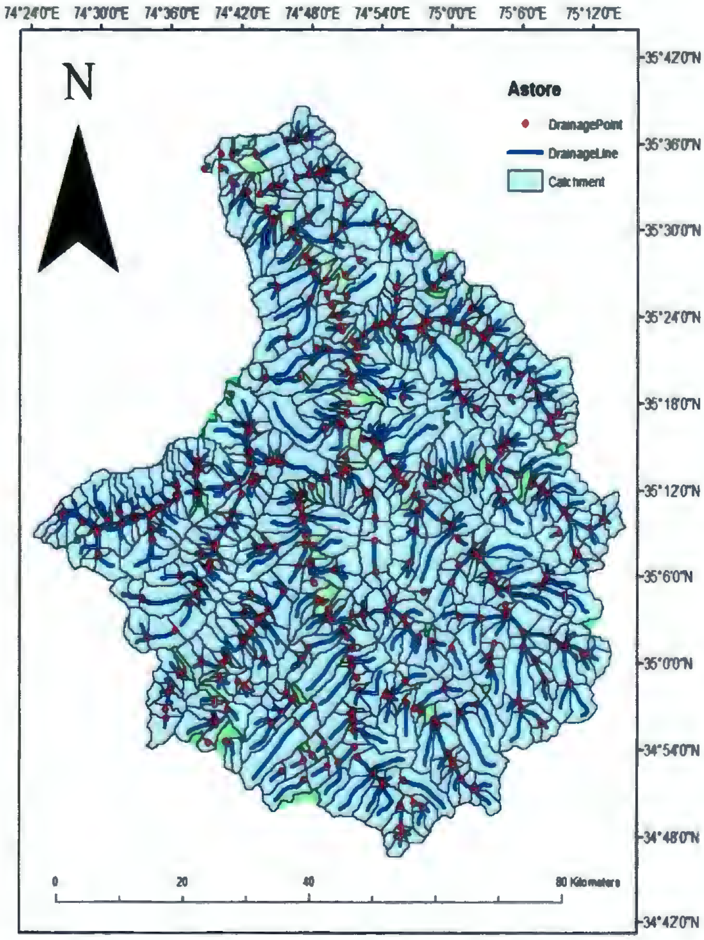

Figure 4.7: Catchment, drainage points and drainage lines of Astore

4.2 Criteria Analysis for potentially dangerous glacial lakes

After identification and indexes the next objective was to classify and prioritize them on the basis of their potential risk. For this purpose, criteria analysis was done in order to meet the objective. As there is no standard index existing in order to define a lake as potentially dangerous one, so the criteria was developed with the help of available literature. Due to high altitudinal, climatic and topographic variation it is difficult to develop a standard index for potentially dangerous lakes. For high altitudinal areas like Northern glaciated region there are some general rules that were adopted in order to identify the vulnerable lakes. Surrounding condition of area, physical characteristics of lakes, condition of associated mother glacier, altitudinal and topographic variations, was extracted through image interpretation and analysis. After image interpretation and analysis it was validated from Google earth.

1- One of the important attribute in defining a lake especially in the perspective of GLOF is lake extent. Lakes which are associated to any hanging glacier at higher altitude are mainly critical as possessing potential hazard of out bursting in case of any avalanche occurrence. Geo- referenced shape files provided by NARC were used as referenced data for mapping lakes over Landsat satellite image of 2014 for 196 lakes. The lakes were cross checked and clearly visible lakes were digitized, while partially visible lakes were re-digitized and confirmed with the Google Earth imagery acquired on 14 December 2015 using spatial information. Threshold values for NDWI and NDVI were defined and lakes were overlaid over them. While doing crosschecking and re digitizing 64 new lakes were identified in Astore basin in year 2015. They were validated through criteria analysis and each of the previously identified 196 and newly identified 65 lakes were individually checked by '***Criteria analysis***'. Criteria was developed on the basis of attributes, i.e., *lake type identification* either it is erosion, moraine, blocked valley, criqure or supra-glacial lake, for proper interpretation as the "Type" information gives the evidence of past GLOF activities. *Activities of supra glacial lakes* where Closely associated supra-glacial lakes were carefully examined as they lead to a large lake with supplementary water volume. *Dam condition* was analyzed by using Google Erath imagery acquired on 14 December 2015. *Condition of associated mother glacier* and amount of debris was carefully examined. *Physical condition* of the surrounding area of each lake was individually evaluated. *Threat of ice and rock sliding*, was also kept in mind while assigning the status of potentially dangerous or at risk.

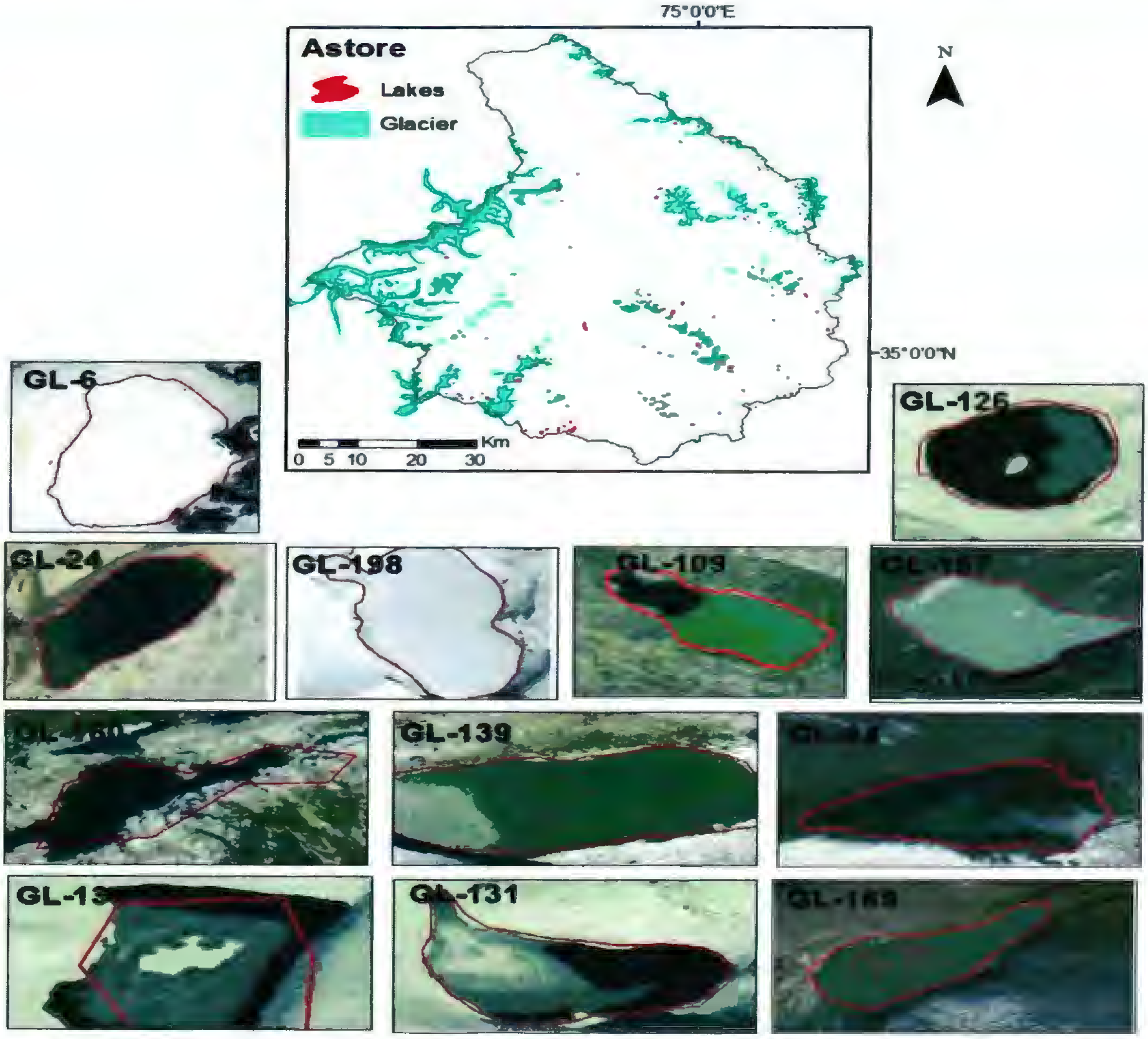

Figure 4.9: Lakes at Risk

Lake Number	Latitude	Longitude	Elevation	Area	Remarks
Ast_gl_126	74°48E	34°50N	17817	3973	At the ridge of massive glacier, have potential to increase the flow of Astore river.
Ast_gl_131	74°47E	34°50N	13652	3893	Large lake surrounded by adjacent lakes can cause flood
Ast_gl_134	74°45E	34°50N	8170	3977	At glacier terminus preceded by large lake.
Ast_gl_160	74°40E	34°55N	236049	3699	In contact with large glacier
Ast_gl_189	74°36E	35°16N	89785	3595	Followed by hanging glacier
Ast_gl_84	74°57E	35°4N	264262	4325	Followed by a large hanging glacier
Ast_gl_24	75°9E	35°16N	54730	4769	Followed by large hanging glacier
Ast_gl_6	75°2E	35°25N	23528	4732	Near hanging glacier
Ast_gl_187	74°33E	35°10N	8341	3752	Near a settlement
Ast_gl_139	74°48E	34°53N	5770	3539	Near glacier ridge surrounded by massive glacier
Ast_gl_109	74°57E	34°52N	64377	4250	Large lake size
Ast_gl_198	75°03E	35°18N	16795	4968	Large lake, near the massive glaciers, surrounded by numerous small lakes, on the risk of avalanche.

Table 1.2: Showing the detail of lakes at risk

Among these 12 lakes one lake was selected as potentially most dangerous one because of its physical and surrounding condition. It lies at 75°03E latitude and 35°18N longitude at 16795 elevation.It has the potential to create catastrophic effect in downstream community. Water can affect the agriculture fields of resident as well as there is a lot of risk of death and property loss. In order to find out the exact outburst potential HECRAS hydrological model was used. Hydrological Engineering Center River System (HECRAS) is basically one dimensional mathematical model used to hydraulic calculations, steady and unsteady flow of river. It is specifically designed to process geo-spatial data in order to compute outburst of any water boundary. Contour and spot elevations were used in order to prepare Triangulated Irregular Network (TIN) In Arc Map GIS. Stream centerline, banks, flow paths and cross sections were prepared In HEC-GeoRAS. For upstream and downstream boundary conditions were defined. Correspondingly, for different return periods input for flood discharge was also given. For the better results Steady flow analysis was done. Water surface profile generated as a result is used to visualize flood inundation depth and boundaries.

4.3 Results of Hecras

Results revealed that river is 35 km long and in case of lake out bursts flash flood will hit settlements and agriculture field within 120 minutes. Lake number 198 has potential to create conditions just like Attabad lake which was formed in Hunza back in 2009.

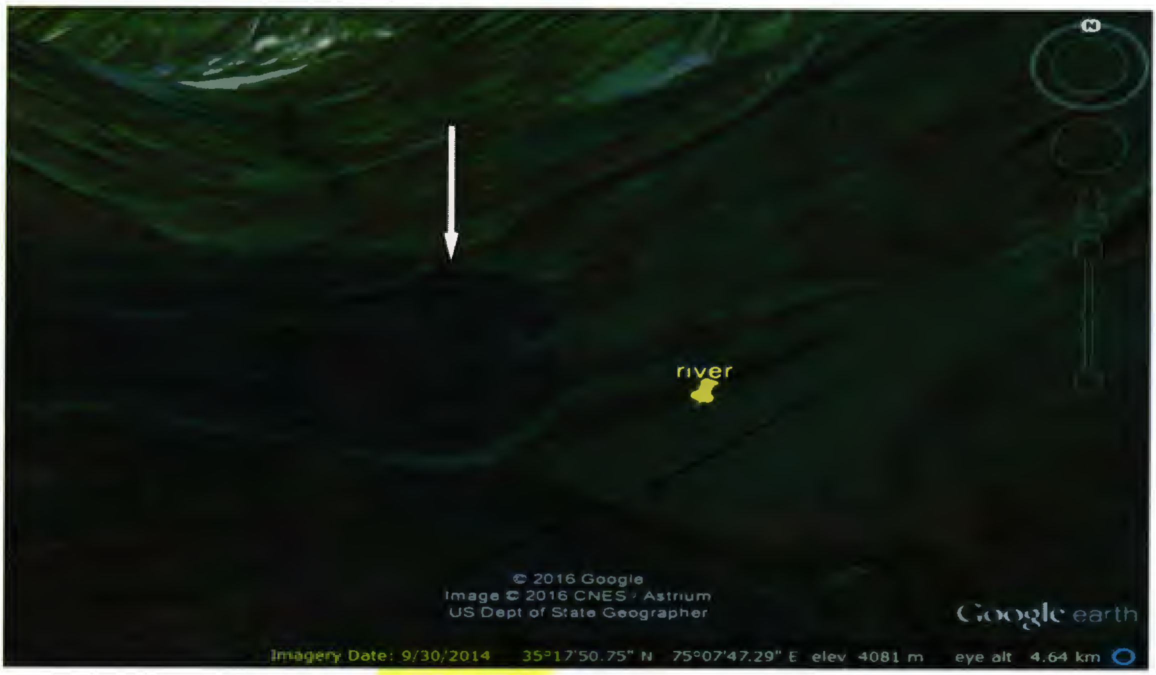

Figure 4.10: Image showing rock sliding site on the river way

There is lot of potential of rock sliding and ice sliding as well. It will increase the volume of potentially dangerous lake in case of outburst or avalanche. As a result it will break the water boundary of surrounding lakes.104 cross sections were developed over 35 km long river. All cross sections were then manually adjusted by taking the help of Google Earth imagery in order to evaluate the flood inundation properly

Inundation area was identified with the help of cross section map developed on 35km long river. Three floods peaks were generated by HECRAS model. In case of worst out breach 30,000 cusecs water will be generated which will further flood away all the settlements, agriculture fields and roads.20,000 cusecs water flood will be generate in case of medium flood and 10,000 cusecs water will generate in the case of low flood zone. Model out put showed that the complete flood wave will drain in to main Astore river with in 90 -100 minutes if generated from lake.

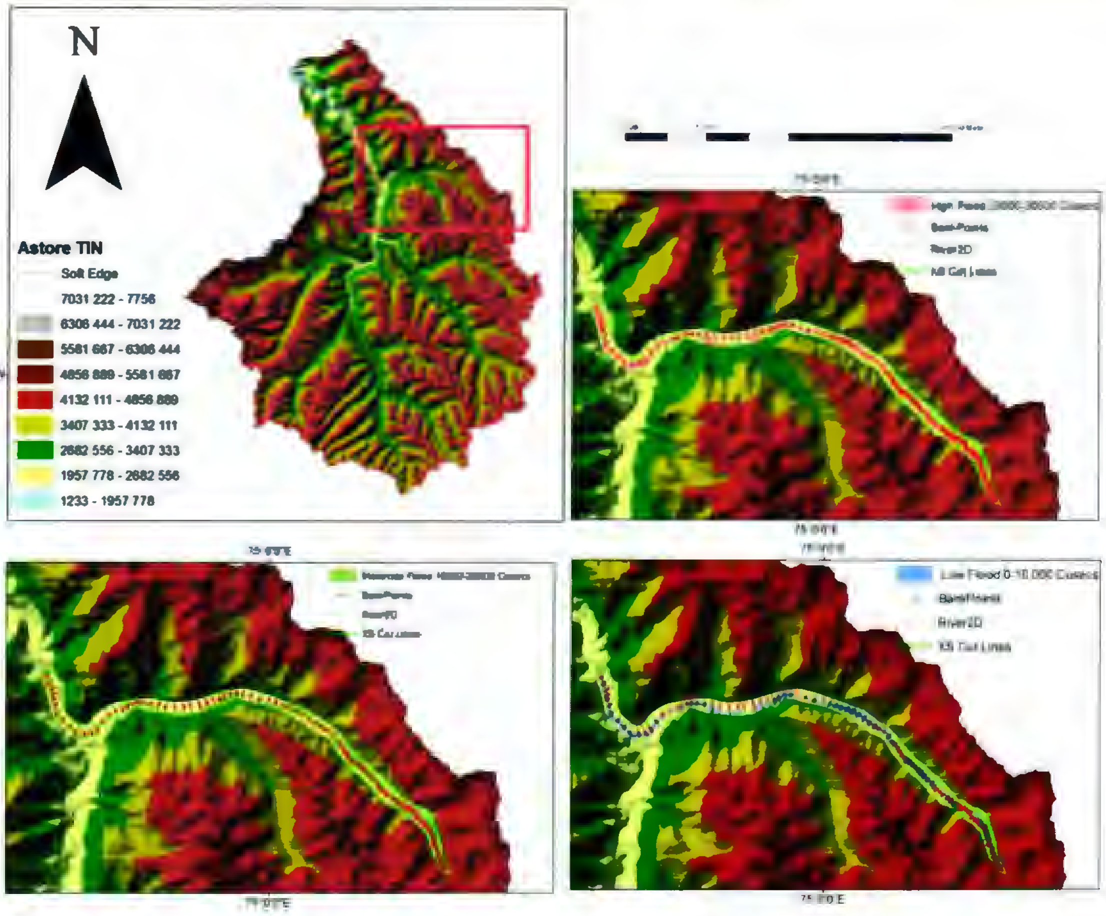

Figure 4.11 2D view of flood inundation

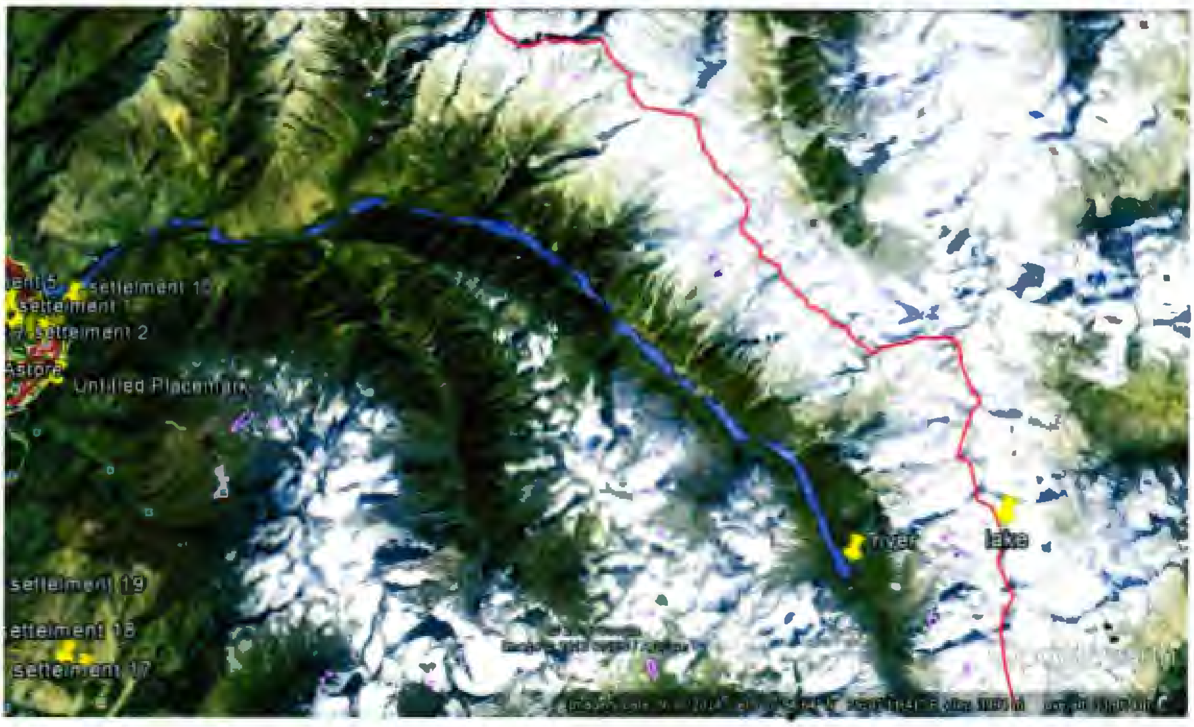

Figure 4.12: 3D view of the inundated area

The inundation map shows that some parts of the river, especially in low and moderate level, does not get flooded As a result of high frequency inundation 3 villages will effects as a result of glacier lake outburst flood Ramkha, Khangrool, Urdong respectively. The flood wave varies in depth and velocity at different locations of the flood plain. The area of the flood wave at this location was estimated to be 30000 sq ft and the flood has been simulated to reach at this location within 87 minutes. Therefore, people may not get enough time to vacate the area before the arrival of the flood wave along with their livelihood.

Limitation of study

One of the major limitations of this study is quality of Digital Elevation Model and terrain condition. Due to coarse resolution of DEM accurate inundation especially in high elevated areas was a difficult task. More ever the cross sections which were developed using the DEM also affect the result. Hence there is a dire need of high resolution DEM especially in high elevated areas.

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Conclusion and Recomendation

5. Conclusion and Recommendations

The present study was conducted for identification of glacial lakes and Pritoize them on the basis of their risk assessment. . Lakes mapping was done in GIS and are validated by Google Earth imagery. Criteria Analysis was used in order to evaluate the lakes at risks. Results revealed that there are total 261 glacial lakes among them 11 are at risk and one is potentially dangerous. Climatic parameters, physical condition of surrounding area and risk of rock sliding was also kept in mind while doing classification. The biggest lake identified covered an area of 4968 (m)^2 has potential to create conditions just like Attabad lake back in 2009. In order to measure the outburst potential of vulnerable lake Hecras hydrological model was used . Inundation area was identified with the help of cross section map developed on 35km long river. Three floods peaks were generated by HECRAS model. In case of worst out breach 30,000 cusecs water will be generated which will further flood away all the settlements, agriculture fields and roads.20,000 cusecs water flood will be generated in case of medium flood and 10,000 cusecs water will generate in the case of low flood zone.

5.1.Recommendations

The integration of satellite remote sensing coupled with GIS techniques proved useful for the study of glacial lakes and potential dangerous glacial lakes in the glaciated region of Astore basin. The information generated through this study would provide base for future monitoring of glacial lakes and GLOFs in the glaciated region for planning and prioritizing disaster mitigation efforts in the region. Policy linkage for potentially dangerous glacial lakes and adaptation measures including developing engineering structures and establishing GLOF early warning systems along the downstream are also required. As flash floods are accepted as common phenomena affecting the livelihood of most of the remote mountain villages, there is always a need to raise public awareness of risks, strengthen communities' preparedness and resilience and develop capacity building plans for local communities and planners in disaster risk management and early warning system to cope with high risk of GLOF hazards in this region.

References

A. Kaab, C. H., L. Fischer, S. Guex, F. Paul, I. Roer, N. Salzmann, S. Schlaefli, K. Schmutz1,D. Schneider1, T. Strozzi and Y.Weidmann. (2005). Remote sensing of glacier and permafrost-related hazards in high mountains: an overview. *Natural Hazards and Earth System Sciences, 5*, 527-554.

AKBAR, M. (2013). *Forest Vegetation and Dendrochronology of Gilgit, Astore and Skardu Districts of Northern Areas (Gilgit-Baltistan), Pakistan.* (degree of doctor of Philosophy), Federal Urdu University of Arts Science and Technology, karachi, Karachi-75300, Pakistan.

Ali, S., Li, D., Congbin, F., & Khan, F. (2015). Twenty first century climatic and hydrological changes over Upper Indus Basin of Himalayan region of Pakistan. *Environ. Res. Lett., 10*, 1748-9326.

Ashraf, A., Roohi, R., Naz, R., & Mustafa, N. (2010 to 2011). IDENTIFICATION OF GLACIAL FLOOD HAZARDS IN KARAKORAM RANGE USING REMOTE SENSING TECHNIQUE AND RISK ANALYSIS. *A scientific journal of COMSATS – SCIENCE VISION, 16-17.*

Ashraf, A., Roohi, R., Naz, R., & Mustafa, N. (2014). Monitoring cryosphere and associated flood hazardsin high mountain ranges of Pakistan using remote sensing technique. *Nat Hazards, 73*, 933-949.

Barclay, J. R., & Walter, M. T. (2015). Modeling denitrification in a changing climate. *Sustainability of Water Quality and Ecology, 5*, 64-76.

Berthier, E., Arnaud, Y., Kumar, R., Ahmad, S., Wagnon, P., & Chevallier, P. (2007). Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India). *Remote Sensing of Environment, 108*, 327-338.

Carrivick, J. L. (2010). Dam break – Outburst flood propagation and transient hydraulics: A geosciences perspective. *Journal of Hydrology, 380*, 338-355.

Chen, C., Xu, C., Chen, Y., Li, W., & Liu, J. (2010). Response of glacial-lake outburst floods to climate change in the Yarkant River basin on northern slope of Karakoram Mountains. *Quaternary International, 226*, 75-81.

Christian Huggel, A. K. a. N. S. (2006). EVALUATION OF QUICKBIRD AND IKONOS IMAGERY FOR ASSESSMENT OF HIGH-MOUNTAIN HAZARDS. *EARSeL eProceedings, 5*(1).

Christian Huggel, W. H., Andreas Kääb, Daniel Bieri and Shaun Richardson. (2004). An assessment procedure for glacial hazards in the Swiss Alps. *Can. Geotech, 41*, 1068-1083.

Cornwella, K., Norsbyb, D., & Marstonc, R. (2003). Drainage, sediment transport, and denudation rates on the Nanga Parbat Himalaya, Pakistan. *Geomorphology, 55*, 25-43.

D.J. Quincey, S. D. R., A. Luckman,R.M. Lucas,J.M. Reynolds,M.J. Hambrey, N.F. Glasser. (2007). Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. *Global and Planetary Change, 56*, 137-152.

Das, S., Kar, N. S., & Bandyopadhyay, S. (2015). Glacial lake outburst flood at Kedarnath, Indian Himalaya: a study using digital elevation models and satellite images. *Nat Hazards, 77*, 769-786.

Dastagir, M. R. (2015). Modeling recent climate change induced extreme events in Bangladesh: A review. *Weather and Climate Extremes, 7*, 49-60.

Early Warning Systems, Monitoring and GLOF Mitigation. *Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment*, 14-20.

Gardelle, J., Arnaud, Y., & Berthier, E. (2011). Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. *Global and Planetary Change, 75*, 47-55.

H. Frey, Huggel, C., Paul, F., & Haeberli, W. (2010). Automated detection of glacier lakes based on remote sensing in view of assessing associated hazard potentials. *Grazer Schriften der Geographie und Raumforschung, 45*, 261 - 272.

Hussain, S. H., & Awan, A. A. (2009). *Report for National disaster management authority on causative mechanisms of Terrain movement in Hunza Valley*. Retrieved from

Khanal, N. R., Hu, J.-M., & Mool, P. (2015). Glacial Lake Outburst Flood Risk in the Poiqu/Bhote Koshi/Sun Koshi River Basin in the Central Himalayas. *BioOne, 35*(4), 351-364.

Kumar, B., & Prabhu, T. S. M. IMPACTS OF CLIMATE CHANGE: GLACIAL LAKE OUTBURST FLOODS (GLOFS). *Geomatics Solutions Development Group (GSDG)*, 81-102.

Martin Margold, K. N. J., Arjen P. Stroeven, John D. Jansen. (2011). Glacial Lake Vitim, a 3000-km3 outburst flood from Siberia to the Arctic Ocean. *Quaternary Research*(76), 393-396

McKillop, R. J., & Clague, J. J. (2007). A procedure for making objective preliminary assessments of outburst flood hazard from morainedammed lakes in southwestern British Columbia. *Nat Hazards, 41*, 131-157.

mek, V. t. V., Klimes, J., Emmer, A., & Benesˇova, M. (2015). Geomorphologic impacts of the glacial lake outburst flood from Lake No. 513 (Peru). *Environmental Earth Sciences, 73*, 5233-5244.

NOOR, A., & KHATOON, S. (2013). ANALYSIS OF VEGETATION PATTERN AND SOIL CHARACTERSTICS OF ASTORE VALLEY GILGIT- BALTISTAN. *Pak. J. Bot., 45*, 1663-1667.

Quincey, D. J., Richardson, S. D., Luckman, A., Lucas, R. M., Reynolds, J. M., Hambrey, M. J., & Glasser, N. F. (2007). Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. *Global and Planetary Change, 56* 137-152.

R.J. Wasson, Y. P. S., Shipra Chaudhary,Manoj K. Jaiswal, P. Morthekai,S.P. Sati,Navin Juyal. (2013). A 1000-year history of large floods in the Upper Ganga catchment, central Himalaya, India. *Quaternary Science Reviews, 77* 156-166.

Rasul, G., Chaudhry, Q. Z., Mahmood, A., Hyder, K. W., & Dahe, Q. (2012). Glaciers and Glacial Lakes under Changing Climate in Pakistan. *Pakistan Journal of Meteorology, 8*(15).

Renji Remesan, I. P. H. (2015). Effect of baseline meteorological data selection on hydrological modelling of climate change scenarios. *Journal of Hydrology, 528*, 631-642.

Richardson, S. D., & Reynolds, J. M. (2000). An overview of glacial hazards in the Himalayas. *Quaternary International, 47*, 65/66

Sanjay K. Jain, A. K. L., R. D. Singh,Anju Chaudhary,L. N. Thakural. (2012). Glacial lakes and glacial lake outburst flood in a Himalayan basin using remote sensing and GIS. *Nat Hazards, 62*, 887-899.

Sharma, S. P. S. I. B.-K. B. S. K. E. (2011). *Climate Change in the Hindu Kush-Himalayas The State of Current Knowledge*. Kathmandu, Nepal.

Shrestha, B. B., & Nakagawa, H. (2014). Assessment of potential outburst floods from the Tsho Rolpa glacial lake in Nepal. *Nat Hazards, 71*, 913-936.

Vaidya, A. Glacial Lake Outburst Flood (India) Mountain Ecosystem Challenges in the Courts.

Vilímek, V., Emmer, A., Huggel, C., Schaub, Y., & Würmli, S. (2014). Database of glacial lake outburst floods (GLOFs)–IPL project No. 179. *Landslides, 11*, 161-165.

Watanabe, T., Lamsal, D., & Ives, J. D. (2009). Evaluating the growth characteristics of a glacial lake and its degree of danger of outburst flooding: Imja Glacier, Khumbu Himal, Nepal. *Norsk Geografisk Tidsskrift Norwegian Journal of Geography, 63*, 255-267.

Worni, R., Huggel, C., Clague, J. J., Schaubd, Y., & a, M. S. (2014). Coupling glacial lake impact, dam breach, and flood processes: A modeling perspective. *Geomorphology, 224*, 161-176.

Worni, R., Stoffel, M., Huggel, C., Volz, C., Casteller, A., & Luckman, B. (2012). Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina). *Journal of Hydrology, 444-445* 134-145.

Xu Wang, F. S., Ai-guo Zhou, Jonas Franke. (2013). Glacier and glacial lake changes and their relationship in the context of climate change, Central Tibetan Plateau 1972–2010. *Global and Planetary Change, 111*, 246-257.

Zaidi, A. Z., & Yasmeen, Z. (2013). Glacial Lake Outburst Flood (GLOF) risk mapping in Hunza River Basin (Pakistan) using geospatial techniques. 191-195.

Zhang, G., Yao, T., Xie, H., Wang, W., & Wei Yang a, b. (2015). An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. *Global and Planetary Change, 131*, 148-157.

Zhang, S. (2013). Estimating the Characteristics of Runoff Inflow into Lake Gojal in Ungauged, Highly Glacierized Upper Hunza River Basin, Pakistan. *Journal of Earth Sciences, 24*, 234-243.

ANNEXTURES

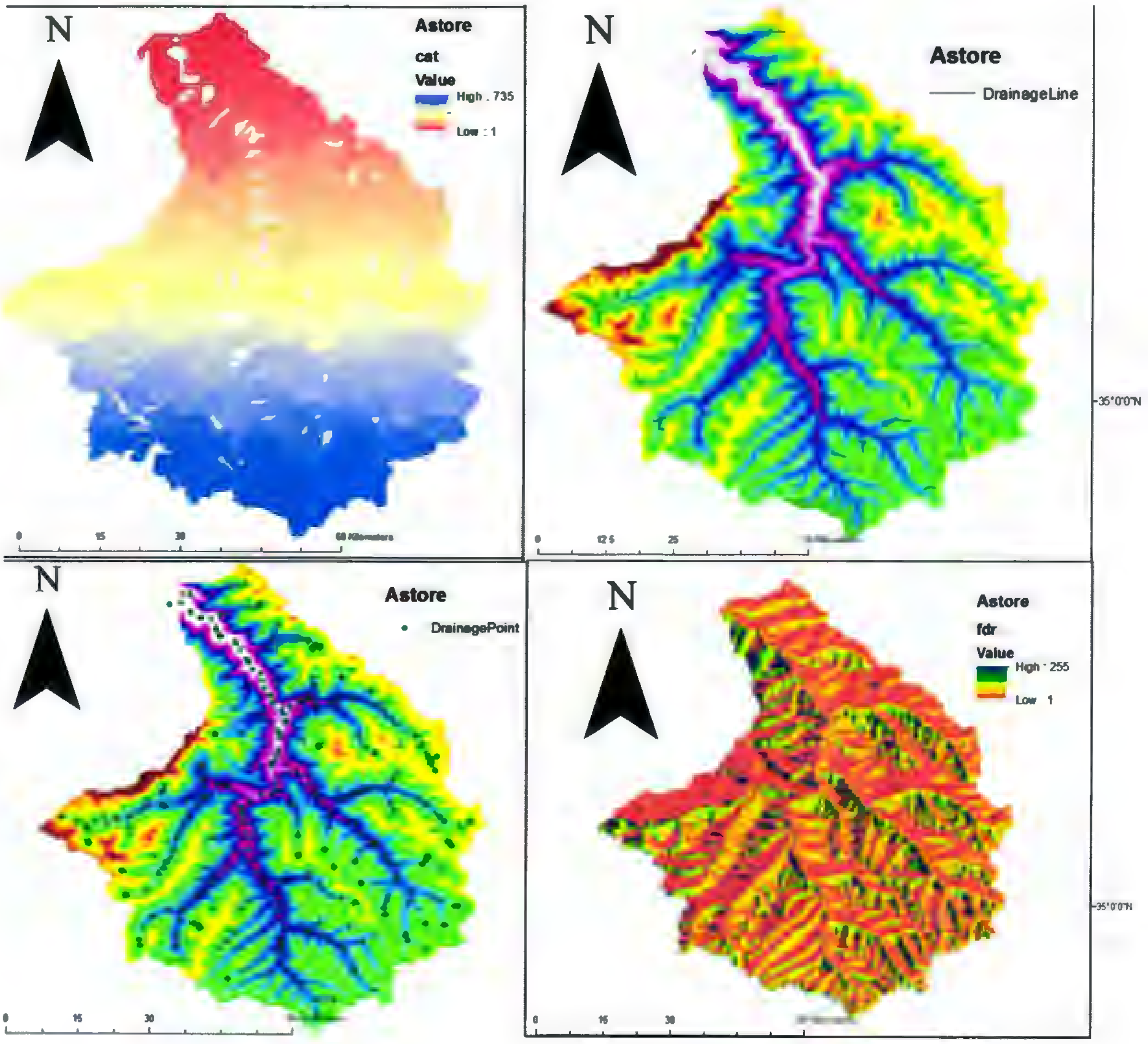
Lake number and Type	Longitude (E)	Latitude (N)	Area(m^2)	Elevation
Ast_gl_1 E	74°5	35°27	14860	4568
Ast_gl_2 E	74°57	35°27	14434	4609
Ast_gl_3 V	74°58	35°25	7956	3676
Ast_gl_4 E	74°59	35°25	4615	4599
Ast_gl_5 E	75°2	35°25	12959	4683
Ast_gl_6 M	75°2	35°25	23528	4732
Ast_gl_7 M	75°	35°25	4164	4802
Ast_gl_8 E	75°5	35°2	15902	4798
Ast_gl_9 E	75°5	35°22	30692	4654
Ast_gl_10 E	75°5	35°22	40350	4632
Ast_gl_11 M	75°6	35°22	7765	4765
Ast_gl_12 E	75°9	35°25	3898	4712
Ast_gl_13 E	75°8	35°20	5488	4653
Ast_gl_14 M	75°9	35°20	16554	4634
Ast_gl_15 M	75°9	35°19	9196	4750
Ast_gl_16 E	75°9	35°18	6026	4713
Ast_gl_17 E	75°9	35°18	16059	4711
Ast_gl_18 E	75°9	35°17	9591	4595
Ast_gl_19 E	75°9	35°18	18637	4734
Ast_gl_20 M	75°1	35°18	5589	4963
Ast_gl_21 E	75°9	35°1	34319	4659
Ast_gl_22 E	75°9	35°16	25823	4585
Ast_gl_23 E	75°9	35°17	5735	4736
Ast_gl_24 M	75°9	35°16	54730	4769
Ast_gl_25 E	75°9	35°15N	13338	4665
Ast_gl_26 E	75°8	35°14N	17008	4601
Ast_gl_27 E	75°8	35°14N	2221	4601
Ast_gl_28 M	75°7	35°15N	11005	4734
Ast_gl_29 M	75°4	35°18N	31696	4591
Ast_gl_30 M	74°56	35°19N	103333	4437
Ast_gl_31 M	74°57	35°19N	30269	4623
Ast_gl_32 E	74°56	35°18N	68155	4206
Ast_gl_33 E	75°58	35°16N	5908	4502
Ast_gl_34 M	75°58	35°16N	8908	4452
Ast_gl_35 M	75°0	35°16N	11064	4585
Ast_gl_36 V	75°4	35°17N	50969	4313
Ast_gl_37 E	75°4	35°16N	14677	4750
Ast_gl_38 E	75°4	35°15N	21293	4519
Ast_gl_39 V	75°5	35°15N	4726	4403
Ast_gl_40 E	75°6	35°14N	10837	4497
Ast_gl_41 E	75°6	35°13N	9805	4556
Ast_gl_42 E	75°9	35°12N	7081	4593
Ast_gl_43 E	75°11	35°11N	18658	4645
Ast_gl_44 E	75°1	35°18N	19735	4561
Ast_gl_45 E	75°11	35°11N	5799	4436

Lake number and type	Longitude (E)	Latitude (N)	Area(m^{20}	Elevation
Ast_gl_46 E	75°13	35°11N	16522	4749
Ast_gl_47 E	75°13	35°13N	21216	4727
Ast_gl_48 E	75°9	35°13N	5680	4534
Ast_gl_49 E	75°9	35°7N	13269	4454
Ast_gl_50 E	75°9	35°9N	59291	4183
Ast_gl_51 L	75°7	35°9N	11651	4324
Ast_gl_52 E	75°5	35°10N	55152	4529
Ast_gl_53 L	75°5	35°9N	15300	4369
Ast_gl_54 V	75°4	35°10N	9318	4034
Ast_gl_55 V	75°4	35°9N	7247	4511
Ast_gl_56 E	75°6	35°7N	10794	4521
Ast_gl_57 E	75°6	35°7N	6713	4489
Ast_gl_58 E	75°8	35°7N	50520	4631
Ast_gl_59 E	75°8	35°7N	20014	4564
Ast_gl_60 E	75°10	35°7N	43051	4524
Ast_gl_61 E	75°12	35°5	23703	4483
Ast_gl_62 E	75°11	35°3	5203	4510
Ast_gl_63 C	75°6	35°2	125658	4420
Ast_gl_64 E	75°9	35°4	7258	4312
Ast_gl_65 E	75°9	34°56	15715	4304
Ast_gl_66 E	75°8	34°56	24604	4303
Ast_gl_67 E	75°8	34°56	4865	4402
Ast_gl_68 V	75°8	34°57	15506	4283
Ast_gl_69 E	75°7	34°58	9641	4303
Ast_gl_70 E	75°7	34°58	19757	4252
Ast_gl_71 E	75°8	34°55	3691	4380
Ast_gl_72 C	75°8	34°55	49146	4343
Ast_gl_73 M	75°7	34°54	10491	4285
Ast_gl_74 M	75°7	34°54	9627	4338
Ast_gl_75 C	75°5	34°53	7717	4306
Ast_gl_76 C	75°5	34°53	24228	4219
Ast_gl_77 E	75°4	34°53	15093	4280
Ast_gl_78 E	75°3	34°58	146053	4260
Ast_gl_79 E	75°2	34°58	79031	4335
Ast_gl_80 E	75°0	35°2	7470	4146
Ast_gl_81 E	75°1	35°4	17063	4404
Ast_gl_82 E	74°58	35°3	13310	4134
Ast_gl_83 E	74°58	35°6	70052	4372
Ast_gl_84 E	74°57	35°4	264262	4325
Ast_gl_85 C	74°57	35°4	87899	4427
Ast_gl_86 E	74°56	35°5	6743	4410
Ast_gl_87 M	74°56	35°5	18485	4460
Ast_gl_88 M	74°56	35°5	75222	4163
Ast_gl_89 M	74°55	35°5	8348	4533
Ast_gl_90 E	74°55	35°6	22384	4481

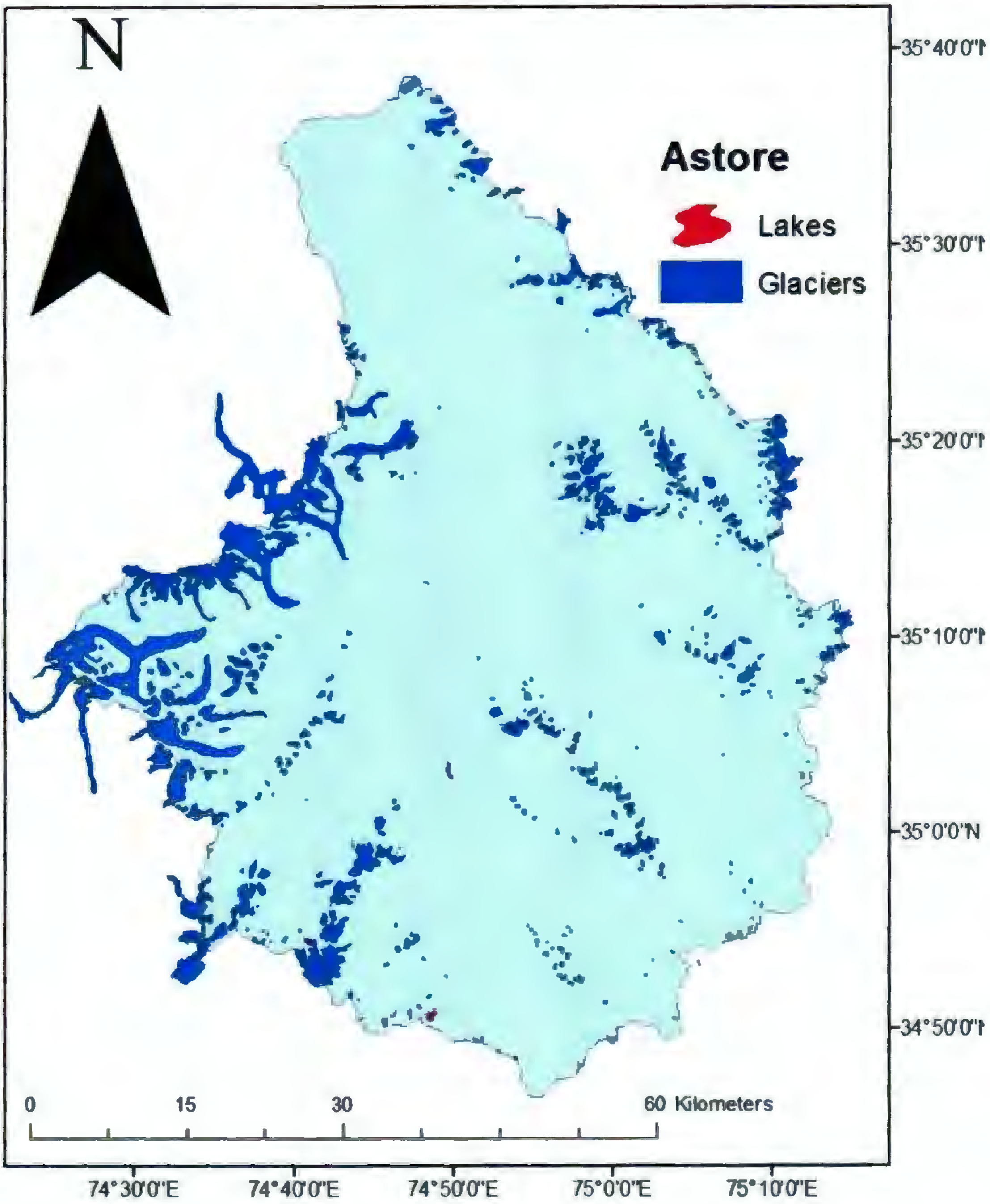
Lake number and type	Longitude (E)	Latitude (N)	Area(m ^{20}	Elevation
Ast_gl_91 E	74°55	35°6	23788	4403
Ast_gl_92 E	74°55	35°7	7653	4614
Ast_gl_93 E	74°54	35°7	11298	4539
Ast_gl_94 E	74°54	35°6	11376	4572
Ast_gl_95 M	74°54	35°5	56970	4382
Ast_gl_96 E	74°53	35°5	5413	4379
Ast_gl_97 M	74°52	35°5	20320	4478
Ast_gl_98 V	74°57	35°3	380	4060
Ast_gl_99 E	75°0E	35°0	38026	3940
Ast_gl_100 E	74°59	35°0	121464	4236
Ast_gl_101 E	74°56	35°0	8646	4349
Ast_gl_102 E	74°56	35°0	23158	4273
Ast_gl_103 E	74°55	35°0	6577	4072
Ast_gl_104 C	75°3	34°57	26086	4385
Ast_gl_105 E	75°4	34°55	14097	4294
Ast_gl_106 E	75°2	34°52	9948	4222
Ast_gl_107 V	75°2	34°53	18644	3818
Ast_gl_108 E	74°59	34°51	3763	4115
Ast_gl_109 E	74°57	34°52	64377	4250
Ast_gl_110 E	74°57	34°52	39861	4266
Ast_gl_111 E	74°56	34°52	30307	4360
Ast_gl_112 C	74°57	34°55	18043	4257
Ast_gl_113 E	74°57	34°55	12880	4256
Ast_gl_114 E	74°56	34°54	9078	4326
Ast_gl_115 C	74°56	34°54	10778	4352
Ast_gl_116 C	74°56	34°54	24171	4335
Ast_gl_117 E	74°55	34°54	16795	4148
Ast_gl_118 E	74°55	34°54	6695	4125
Ast_gl_119 E	74°54	34°55	4085	4212
Ast_gl_120 E	74°54	34°55	22752	4066
Ast_gl_121 E	74°55	34°54	7887	4350
Ast_gl_122 E	74°55	34°54	6582	4206
Ast_gl_123 E	74°55	34°54	30324	4226
Ast_gl_124 E	74°56	34°53	7969	4222
Ast_gl_125 E	74°56	34°53	15773	4227
Ast_gl_126 E	74°48	34°50	17817	3973
Ast_gl_127 E	74°48	34°51	487424	4008
Ast_gl_128 V	74°49	34°52	13220	3364
Ast_gl_129 E	74°48	34°5	7523	3897
Ast_gl_130 E	74°47	34°51	71334	4113
Ast_gl_131 E	74°47	34°50	444401	3893
Ast_gl_132 E	74°46	34°50	113652	3991
Ast_gl_133 E	74°46	34°50	37732	4018
Ast_gl_134 C	74°45	34°50	8170	3977

Lake number and type	Longitude (E)	Latitude (N)	Area(m ^{20}	Elevation
Ast_gl_135 E	74°44	34°50	238784	4022
~~Ast_gl_136 E~~	74°44	34°50	5320	4179
Ast_gl_137 E	74°44	34°50	18392	4212
Ast_gl_138 V	74°44	34°50	13674	4195
Ast_gl_139 M	74°48	34°53	5770	3539
Ast_gl_140 V	74°47	34°54	21220	4249
Ast_gl_141 E	74°46	34°55	34384	3479
Ast_gl_142 E	74°4	34°56	36685	4589
Ast_gl_143 E	74°43	34°56	3341	4522
Ast_gl_144 E	74°43	34°56	8465	4547
Ast_gl_145 M	74°43	34°56	5982	4569
Ast_gl_146 M	74°45	34°58	57558	4643
Ast_gl_147 E	74°45	34°58	10553	4625
Ast_gl_148 E	74°45	34°58	50101	4638
Ast_gl_148 E	74°46	34°59	3745	4375
Ast_gl_149 E	74°46	34°59	13958	4483
Ast_gl_150 E	74°46	34°58	5826	4573
Ast_gl_151 M	74°46	34°59	5703	4510
Ast_gl_152 M	74°46	35°3	12765	2740
Ast_gl_153 V	74°49	35°0	313721	4551
Ast_gl_154 M	74°45	34°59	9174	4430
Ast_gl_155 M	74°44	34°59	10894	4351
Ast_gl_156 M	74°43	34°59	47264	4294
Ast_gl_157 E	74°43	34°59	5958	4503
Ast_gl_158 M	74°42	34°56	28653	4408
Ast_gl_159 E	74°42	34°54	13285	3366
Ast_gl_160 M	74°40	34°55	236049	3699
Ast_gl_161 V	74°40	34°54	23317	3947
Ast_gl_162 E	74°39	34°54	8808	3953
Ast_gl_163 M	74°39	34°54	46979	4232
Ast_gl_164 E	74°38	34°54	9552	4033
Ast_gl_165 M	74°38	34°54	61222	4259
Ast_gl_166 E	74°38	34°55	25362	4100
Ast_gl_167 E	74°36	34°55	12199	4282
Ast_gl_168 M	74°37	34°56	8908	4089
Ast_gl_169 M	74°37	34°58	7190	4089
Ast_gl_170 E	74°37	34°58	13447	4282
Ast_gl_171 M	74°34	34°58	19235	4446
Ast_gl_172 E	74°35	35°0	26079	4563
Ast_gl_173 E	74°38	35°2	6863	3884
Ast_gl_174 V	74°40	35°1	3095	4235
Ast_gl_175 E	74°41	35°3	3440	2593
Ast_gl_176 V	74°48	35°12	5410	2608
Ast_gl_177 V	74°48	35°12	8733	4328
Ast_gl_178 M	74°38	35°2	7190	4412

Annexture 2



Arc- Hydro Maps



Glacial lakes by ICIMOD