GLACIAL LAKES FORMATION, EXPANSION AND DISAPPEARANCE IN GLACIATED REGIONS OF NORTHERN PAKISTAN

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FINAL APPROVAL

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Dedicated to

My Respectable

Ammi, Abbu,

Brothers

&

My elder sister

Shazia Noureen

DECLARATION

I hereby declare that the work present in the following thesis is my own effort, except where otherwise acknowledged and that the thesis is my own composition. No part of the thesis has been previously presented for any other degree.

Date 9-9-2016

Shafia Noureen

بسم الله الرحمن الرحيم

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ABSTRACT

The Glaciated mountainous regions of Northern Pakistan contain the highest concentration of snow and ice in form of Glaciers and *gl.* Lakes therefore it is known as Third Pole having largest repositories of inland cryosphere outside Polar Regions. But during last decade these glacial lakes are under the pressure of an alarming increase in temperature trend which surpassed all the past records resulted in the rapid melting of glacier ice mass, creation and expansion of the *gl.* lakes. The purpose of the present study was to utilized a stepwise approach to analyzed and characterized the glacial lakes and investigated all possible reasons for their formation, expansion and disappearance in glaciated sub basin (UIB) of Northern Pakistan i.e. Swat, Chitral, Gilgit, Hunza, Shigar, Shyok, Indus, Shingo, Astore and Jhelum basin. For this purpose a temporal satellite LANDSAT TM/ ETM + imagery from Google Earth, remote sensing and GIS techniques, topographic and historical data (including photographs, travelling reports and published papers) were used. In this study, a total of 50 glacial lakes were selected with area > 2000 sq.km, out of which 45 lakes were newly appeared while 5 lakes were disappeared during the period of 2001-2013. Results showed that majority of the lakes were Moraine type (included both end & lateral moraine), while some other lakes are erosion lake. Data analysis also showed that the most prominent possible associated risk factors like Earth quake, Lansliding, Glacier recession, River impounding and glacier damming have higher significant correlation with the glacial lakes Formation in glaciated regions of Northern Pakistan.

Finally the correlation of glacial lakes Formation with average rise in temperature and precipitation in ten glaciated sub basin of Northern Pakistan during 2001 to 2013 was also carried out and it was found that glacier recessions and *gl.* Lakes formation has close association with rise value of mean summer air temperature. Therefore during the period of 2001–2013 more gl. lakes formation observed than the period of the 1970s–2001. In this regard field survey is essential to acquire information to validate the findings and to assure the best quality life for the inhabitants of that area.

Key words: Glaciers, UIB, Glacial Lakes, HKH, GLOF

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LIST OF ABBREVIATION

UIB Upper Indus Basin

HKHHindukush-Karakoram- Himalaya

KKH Karakoram Highway

Gl Glacial Lake

GB Gilgit-Baltistan

GISGeographic Information System

RS Remote Sensing

GLOF Glacial Lake Outburst Flood

PMDPakistan Meteorological Department

ICIMOD International Centre for Integrated Mountain Development

LANDSAT Land Resources Satellite

UTM Universe Transverse Mercator

RGBRed Green Blue

FCCFalse Colour Composite

DEM Digital Elevation Model

NIMA National Imagery and Mapping Agency

DMA Defense Mapping Agency

UNDP United Nations Development Programme

UNEPUnited Nations Environment Programme

WAPDAWater and Power Development Authority

IPCC Intergovernmental Panel on Climate Change

NARC National Agricultural Research Centre

PARCPakistan Agricultural Research Council

LIST OF SYMBOLS

maslmeters above sea level

Sq.kmsquare kilometer

Ha. Hectares

& And

% percentage

:Ratio

INTRODUCTION

In South Asia, Pakistan is located between 24°-37°N latitude and 66°-77°E. The Upper Indus basin comprises the western end of long Himalayan range and some parts in the Hindu Kush and Karakoram ranges(HKH) within longitudes 70° 57′ - 77° 52′ Eand latitudes 33° 52′ - 37° 09′ N, stretching over Khyber Pakhtunkhwa and the Gilgit-Baltistan Areas **(Barry, R. G., 2002).** According to the **Chettri*et al.*, 2011** the mountain range of the HKH having a high concentration of ice reserves inform of glacier ice, snow & glacial lakes and also referred to as Asia's Water Tower (e.g. Smiraglia*et al.*, 2007 andKehrwald*et al.*, 2008), and its water utilized for different purposes such as drinking, agriculture, and power production.

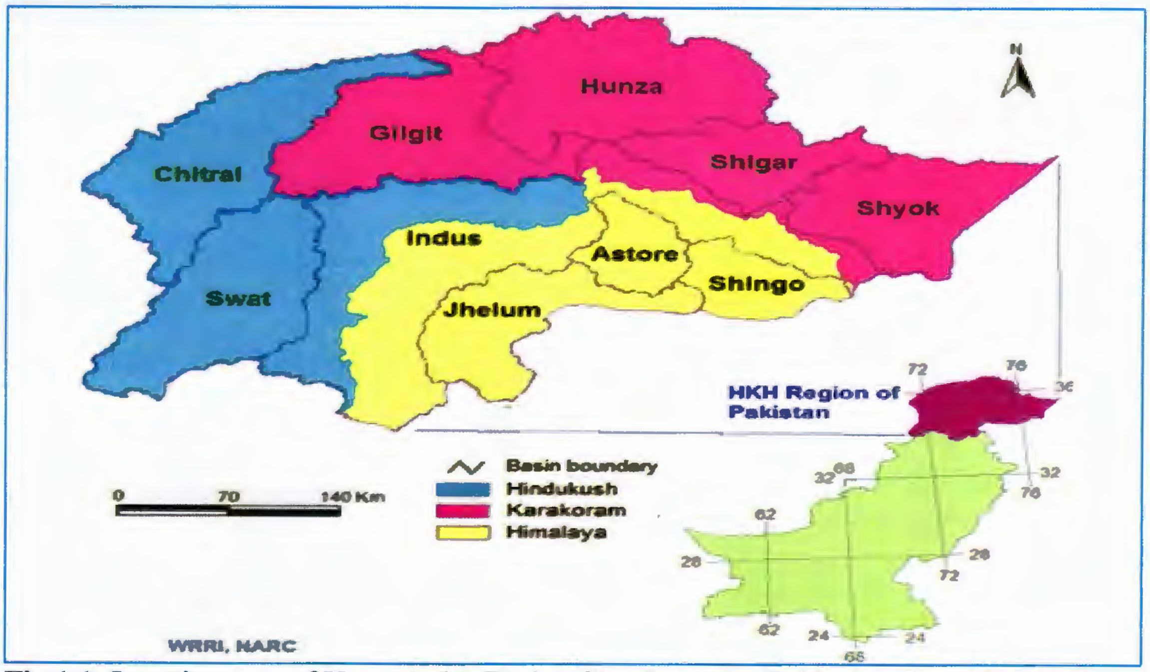


Fig.1.1: Location map of Upper Indus Basin of Pakistan. Available in color online.

It has been found that the most important natural resources in these glaciated Northern regions are Glaciers and Glacial lakes which are reserved or stored as frozen water. These frozen water uses as a fresh water supplier for the survival of more than millions inhabitants as well as in the adjoining plains (APN project, 2004). Different tributaries of numerous glaciers i.e. more than 70 km long feeding the Indus arises from ten sub basin (Barry, R. G., 2002). The glaciated region of UIB consists of numerous lakes scattered at various places. These lakes are formed due to climate and geomorphic changes like the accelerated retreat of glaciers with increasing temperatures, blockage of main rivers and tributaries by mass movement/debris flows etc. (ICIMOD, 2005).Like in many other parts of the world, this region is also famous by recession and permafrost thawing behavior of glaciers which results into developing and disappearing of numerous lakes.

1.1.Glacial Lakes and its outburst Flood (GLOF)

A glacial lake is defined as a sufficient amount of water mass originating from glacier activities and/or retreating processes of a glacier and extending with a free surface either near or away from glacier(Campbell 2004). These lakes are impounded by natural dam like moraine dammed lakes. Occasionally, a moraine breaks, releasing the lake's stored water and discharging large volumes of water with debris, which causes downstream flooding along the river channel. This phenomenon, generally known as a glacial lake outburst flood (GLOF), is one of the most serious disasters to occur in the Himalayan regions of China, Nepal, India, Pakistan, and Bhutan (Y. Ding., 1992).

1.2.Types of Glacial lakes

The lakes are of different types on the basis of their formation named as Erosion, Blocked, Moraine Dammed (Lateral Moraine and End Moraine Dammed lakes), Valley trough, Cirque, and Supraglacial lakes (Campbell 2004).

1.2.1. Erosion lakes

Sometimes lakes are formed due to the accumulation of water bodies in a depression generated due to the glacier recession. Such types of lakes are called Erosion Lakes which may either Cirque type or trough Valley type which are called as stable lakes. These lakes are mostly isolated and far away from the parent glacier.

1.2.2. Supraglacial lakes

The Supraglacial lakes is another type of lakes which is formed on the surface of glacier within ice mass at any position in the form of small ponds that can be shifted, merged or drained through their outlet. These lakes are present in large numbers on glacier surface. Sometimes these small ponds combine together to form one large moraine dammed lake witch store huge volume of water with a high level of potential energy which indicates the danger level of GLOF.

1.2.3 Moraine Dammed lakes

On the other hand when glaciers show its retreating behavior, glacier ice tend to melt or accumulate either its side or lowest part of the glacier surrounded by Lateral Moraine and End Moraines. A Moraine Dammed lake is thus formed. The lake is filled with melt water and rainwater from the drainage area behind the lake and starts flowing from the outlet of the lake even in the winter season when there is minimum flow. Moraines are of two types: an ice-cored moraine, in which glacier ice is not completely melt and covered the moraine or sometimes ice present beneath the bottom of lake which is called dead ice or fossil ice. The second type of moraine called ice-free moraine, in which glacier ice continues to melt, the lake becomes deeper and wider. In this case glacier ice completely melts away and leaving behind the container of thelake water consists of only the bedrock and the moraines.

1.2.4. Blocking lakes

Two factors are responsible for the formation of blocking lakes.one of the most common factors are glaciers which sometimes blocks the branch valley or sometimes branch glacier blocking the main valley as a result lake is born called blocked lakes. The other factors including snow avalanche, collapse and debris flow blockade.

1.2.5. Ice-dammed lakes

An Ice-dammed lake is produced on the side(s) of a glacier, when an advancing glacier happens to intercept a tributary/tributaries pouring into a main glacier valley. As such, an Ice core-dammed lake is usually small in size and does not come into contact with glacier ice. This type of lake is less susceptible to GLOF than a moraine dammed lake. When glacial lake is formed its expansion and disappearance depends on the glacier fluctuation. By considering the lifespan of an individual glacier, it is found that the Moraine Dammed glacial lakes build up and disappear with a lapse of time. The moraine dammed lakes disappear once they are fully destroyed ormother glacier advances again to lower altitudes beyond the moraine-dam position or when debris fills the lakes completely. Such types of glacial lakes are mostly dangerous and unstable from the point of view of the life of glaciers. Generally, moraine dammed lakes are the main reasons for GLOF events.

1.3. Types of Natural dam

Glacial lakes are basically the bodies of water ponded by glaciers due to glacier recession (glacier dammed lake), mudflow and sediment deposition after landslide (landslide dammed lake) or by interfere the flow of river in a potentially dangerous way or river erosion. Glacial lakes are impounded by these different types of natural dams in many areas of the world. The lateral or end moraine dammed lakes have high tendency of breaching because it islocated at the snout of the glacier. During the Little Ice Age, newly formed unstable moraines usually dammed the valley lakes below the glacier. In the natural landscape shaping processes, lakes dammed by glaciers play a prominent role such as glacial lakes present in the western Karakoram are the Arandu-, Batura-, Biafo-, Ghulkin-, Gulmit-, Malungutti glaciers. In addition to the glacier dams in the main valleys, temporary lateroglacial lakes are very common along the large Karakoram glaciers, such as at the Khurdopin, Yazghil or Chogolungma glaciers (Iturrizaga, 2002a). While in tectonically active mountain regions lakes are mostly dames by landslise which mostly present in different parts of the world (Costa and Schuster, 1988; Korup, 2004; Evans et al., 2011).In some cases valley river either temporary or completely blocked by landslide and impounded a lake.

1.4. Glacial Lakes in Glaciated Upper Indus Basin (2005 & 2013 Scenario)

ICIMOD conducted an inventory in 2013 with the help of RS/GIS technique which indicates increase in numbers of glacial lakes in all the river basins except Swat and Chitral when compared with the findings of previous lakes inventory of 2005 (Figure 1.2).In the previous inventory, total of 2420 glacial lakes were identified that cover surface area of about 126sq.km in the glaciated UIBof Pakistan. The present inventory exhibits total of 3044 glacial lakes covering area of about 134.8sq.km in the ten river basins. The increase in lakes in most of the river basins can be attributed to several factors like higher precipitation, rapid melting of source glaciers due to global warming in this region besides better quality of the imageries used.For present study,the lakes associated with perennial snow and ice, originate from glaciers, and in some cases the isolated lakes found in the mountains and valleys far away from the glaciers are considered.

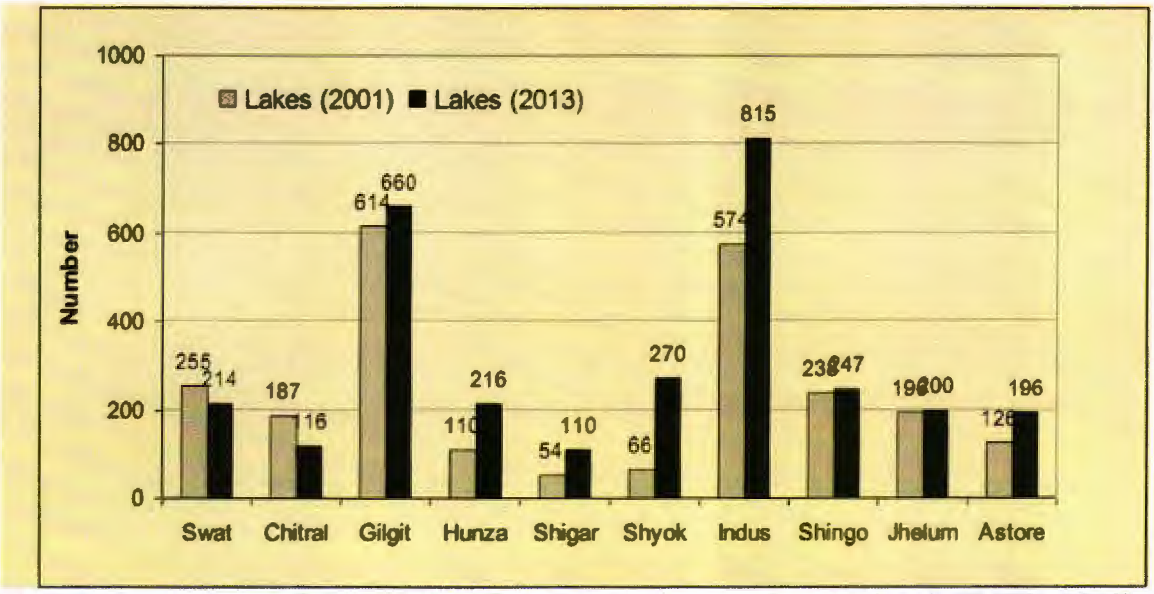


Fig.1.2: Comparisons of glacial lakes of previous and current inventories. (ICIMOD, 2013)

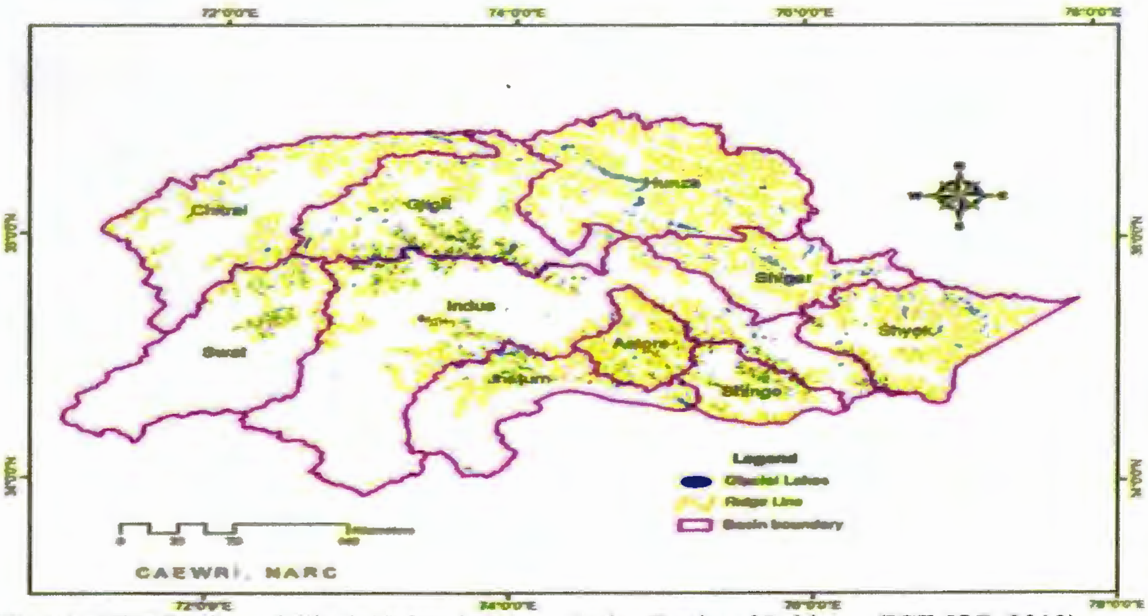


Fig.1.3. Distribution of Glacial lakes in Upper Indus Basin of Pakistan (ICIMOD 2013)

1.5. Association of Climate Change with Glacial lakes formation

The glaciers and glacial lakes are the fundamental parameter for indicating the climate changes, as they remain sensitive to extreme climatic conditions as reported by their continuous retreat. It has been found that Global warming is the main cause of glacier recession in different parts of the world including the Himalaya. For example since the second half of 20th century, the phenomena of global warming has become a burning issue because at that time glaciers of Northern region of Pakistan start retreating and developing into lakes on the recent glacier terminus **(Mool et al., 2001)**. Surging, retreating and fast melting of glaciers. In these high mountains glaciers shows different behavior like (Surging, retreating and fast melting) with exposal of terminal moraines resulted in glacial lakes formation at the terminus of end moraines. It was also reported that global warming during the last 100-150 years has been associated for large scale destabilization of Northern mountain landscape systems and boost up certain catastrophic processes like formation of many moraine- and glacier dammed lakes, largely as a result of abrupt glacier ice loss **(Evans and Clague, 1993).**

1.6. Climate Change and Glacial lakes Expansion

During the last half of the twentieth century, generation of water due to the faster rate of ice and snow melting, in these lakes has been increasing rapidly under the impact of global warming.Awan, (2002) also reported that the process of lakes formations are closely associated with glacier recession and climate change especially an increase in global warming is particularly responsible for glacial lakes formation and expansion. This situation has become more significantand important over the past century due to increase in number of glacial lakes with increasing rate of glacier recession which in turn responsible for catastrophic flood **(LIGG/WECS/NEA. 1988 and Mool et al., 2001).Haeberli and Hohmann, (2008)** also reported that in the overdeepened parts of the exposed glacier bed or behind the moraine dam some lakes tend to developed which is calledproglacial lakes. Such new lakes are attractive elements in a landscape and compensate to a certain degree the loss of attractiveness from glacier disappearance **(Haeberli and Hohmann, 2008).**

1.7. Systematic methods to assess Glacial Lakes

Due to the rugged topographic variation and harsh climatic conditions in these areas it is not an easy task to visit these lakes and observed its changes on ground location. That's why no detailed investigation of glacial lakes formation & disappearance or its relation to climate has taken place in ten catchments of Indus basin. Therefore, an assessment of glacial lake variation and its associatedhazards is a top priority in this region. Different techniques and procedure has been adopted by different researchers to monitor these glacial lake associated hazards. For this purpose remote sensing(**Huggel et al. 2002; Ka¨a¨b et al. 2005; Allen et al. 2008**), geographic information systems (GIS) (**Huggel et al. 2003, 2004b**) and statistical (**McKillop and Clague 2007b**), empirical-based (**Huggel et al. 2004a; McKillop and Clague 2007a**) approaches has been used.The present articles attempt to solve this problem by paying attention on the reasons of the glacial lakes development and disappearance. For this purpose, multitemporal satellite imagery and historical data is used to analyze the pattern of lakes development. This methodology is highly useful for better evolution of the glacial lakes and distribution within the catchments, as well asthe climatic variables and their impacts on glacial lakes formation is also addressed by using the meteorological data from stations near our study area.

1.8. Description of study area:

The study area focus in this study is the Glaciated Upper Indus Basin (UIB) because of its hydrologic importance to Pakistan and its susceptibility to landsliding. Geographically, total area of the river basins is about 128,730.8sq.km. It is basically the largest river basin of Pakistan because the main river in this basin is Indus River which comes from Jammu Kashmir then it joined through different tributaries to ten small river catchments of this basin which is bounded in west by Swat River basin, in the north by Gilgit and Hunza River basins, in the northeast by Shigar River basin and in the east by Shyok River basin. In the south the Shingo, Astor and Jhelum River basins are located. Besides this UIB also contain many large and small glaciers which covers almost 11.7% of the total geographic area of the ten basins.(**PARC & ICIMOD, 2005**). The total ice reserves in the form of glaciers and glacial lakes in UIB are about 2,738.5 km^3. The major portion of these ice reserves are contained by Shyok, Hunza and Shigar basins which is about 83%. However the majority of HKH region is covered by UIB basin so we used both terms alternatively in this study.**The specific objectives of this research study are:**

(i) To find the causes of glacial lakes formation, expansion and disappearance of already existing Lakes in glaciated regions of Pakistan.

(ii) To identify the changes in glacial lakes which are likely to form, expand or disappear in near future and to assess their distribution and evolution in ten sub basin.

(iii) To analyze climate change impact on glacial lakes and its behavior.

LITERATURE REVIEW

1.1.1. Association of Climate Change with Glaciers recession

High mountain environments constitute many glaciers and glacial lakes which are highly dynamic and sensitive systems therefore they known as primary indicators or barometer of climate change (e.g., Beniston, 2003; Huber et al., 2005; Harris et al., 2009). The rising trend in the summer temperatures observed for the last four decades in Himalayan region of Pakistan has affected the overall coverage and reserves of the glaciers. This has resulted in changing behavior of the glaciers and their associated lakes. In the past two decades of twentieth century, the anthropogenic forcing of climate change are considered as a main cause of an abrupt rise in temperature which ultimately leads to global warming,especially during the period spanned over 1995–2006 (Mann and Jones, 2003; Thorne et al., 2003; Trenberth et al., 2007). Among these anthropogenic activities are the emission of high amount of GHGs which leads to climate change in terms of increase in temperature, change in precipitation pattern and probably a rise in the frequencies of extreme events by disturbing the radiative balance of the earth (IPCC, 2001; Meehl et al., 2007; Tett, et al., 2007).

Several previous studies also reported this rise in temperature in previous century and now it is proved by meteorological data which recorded 0.07°C per decade rise in temperature (Folland et al., 2001; Jones and Moberg, 2003). On the other hand results of similar study by Chaudhry et al., 2009 showed that Pakistan experienced 0.76°C rise in temperature during last 40 years. While during the same time period,it was recorded as 1.5°C rise in glaciated mountain. Besides this in the twentieth century an increase of ~ 0.98 % per decade of globally observed annual precipitation has also been reported (New et al., 2001). The most severe threat of this rise in temperature & precipitation is related to the rapid melting of glaciers and lakes formation.

Worldwide much of the glacier retreat has been observed at tropics, humid mid-latitudes and polar regions over the last few decades (WGMS, 2008; Kaser, 1999; Aizen et al., 2007b; Lambrecht and Kuhn, 2007). The results of IPCC, (2007) considered the evident atmospheric temperature rise was the main reason for much of this retreat. Global warming involves an unprecedented speeding up of the rate of glaciers recession in mountain ranges all over the world (GCOS, 2004; Lemke et al., 2007). Now it has been proved that in many locations of the world glacier recession has accelerated in recent decades (Zemp et al. 2008). Hence, many scientific researchers now believes that climate change is a real phenomenon which is continuously happening (IPCC, 2007; Saier, 2007).

1.1.2. Association of Glacier recession with Lake Development

In Northern area glacier and its associated lakes are of great importance as it is main source of freshwater that benefits hundreds of millions of people downstream. Approximately 80% of the total flow of the Indus River in the summer season coming from the glacier and ice melt water in UIB (PARC, 2005). But unfortunately this region is facing the one of the serious problem of water security due to glacier depletion under the effect of global warming (IPCC 2007). It has been widely approved thatthroughout the world glaciers recession and shrinkage occurred due to global climate change (Chen g, 1996; Allison e t al., 2001; IPCC, 2007).However, the characteristics and retreating rate of glaciers are different across the world.

In UIB a close association has been reported in Glacier depletion and lakes development (Baker, 1996). It is widely analyzes or observed that majority of the lakes in glaciated UIB is developed on or near to the glacier due to glaciers activity (ASHRAF, A. et al., 2008). Glaciers associated lakes are continuously developed or expanded due to glacier recession in mountainous areas of the world which leads to an increasing risk of lake outbursts. This phenomenon of lake Outbursts is known as Glacial Lakes Outburst Flood (GLOF) which pose serious hazard to downstream inhabitants and their livestock (Clague and Evans 2000; Huggel et al. 2003, 2005; Iwata et al. 2002; Ma et al. 2004; Popov 1988; Richardson and Reynolds 2000). Another research also reported that an abrupt rise in temperature & precipitation on snow and glaciated environment of UIB (A. ASHRAF et al., 2011). These are the factors which are clearly responsible for lakes formation, expansion and outburst flooding.

According to the Bolch*et al.,* (2012) Glacier retreat leads to the creation of many new melt water lakes on lower section of such type of glaciers. It has been concluded from the results of recent researchers that majority of the lakes are developed at glacier terminus after glacier recession in the phase of accelerated global warming (Mool *et al.,* 2001). Narama*et al*., (2009),reported that under atmospheric warming, the number & size of glacier lakes have been increasing reflecting glacier melting in northern mountains of Pakistan (Aizen, et al., 2006; Narama et al., 2006; Bolch, 2007; Ku-tuzov and Shahgedanova, 2009; Narama et al., 2010a) and posing growing threats to people living in and near the mountains. The unstable lakes can pose threats to local population(Costa and Schuster, 1988).

1.1.3. Glacier surge and Lake Development

Meyer *et al.,* (1993), for the first time reported that gl. lakes are formed on the glacier terminus due to the recent retreating processes of glaciers. And later on this is proved by Ashraf, A. et al., (2008) who define the process of gl. lakes formation, according to him when glacier terminus start shrinking/retreating leaving behind lateral or end moraine which later on dammed the melt water and developed into lakes. Such lakes may present at the bottom or on top of these glaciers. The importance of this situation has magnified over the past century due to the increased number of glacial lakes. There are many glaciers in UIB which shows geomorphological evidence of retreat and rapid down wasting such as ChogoLungma and Hunza's glaciers show a similar surface down wasting pattern but at different rates. Because the moderate to large size glaciers showhighest retreat rates including Batura, Gulmit, and Passu. Conversely, other large glaciers such as Hispar, Barpu, and Bualtar exhibit lower retreat rates (Roohi, R., 2007).

Similar study on glacier retreat and thinning (downwasting) was also conducted by O'Connor and Costa (1993) and more recently, by Clague et al., (2012) and S. Shakir*et al.,(*2010). Above these studies revealed that climate change, glacier recession and lakes formation are interlinked in such a way that due to climate change glaciers and snow start melting by retreating or shrinking as results lakes will form. The retreating characteristics of glaciers are important parameters in order to study the climatic variations and glacier fluctuation (Kaser, 2001; Wagnon et al., 2001). On the other hand,retreating rate of glaciers was also determined by ICIMOD i.e. 10m to 60m per year and many small glaciers have already disappeared (Bajracharya et al. 2007).

These findings were further confirmed bytemporal comparison of satellite imageries conducted by G. Vassena., (2007), at or near the glaciers of HKH there is an increasing tendency of lakes to develop and expand. There are many evidences on glacial lakes formation and expansion in UIB as reported by Hewitt (1982) including the growth and disappearance of Virjerab Lake in the Hunza region as a result of glacial shift.

Another study revealed that lakes formation is not only associated with retreating behavior of glacier but also due to the surging behavior of glaciers and some ice dams may have been the result of glacier surges (Meyer et al. 1993). In UIB many examples of surging glaciers and lakes formation have been also recorded (Khan 1994). Thirty glaciers are known to have advanced across major head water streams of the Indus and Yarkand Rivers. In 1977 the Balt Bare glacier above the Shiskat village released a surge of melt water and the 20m high dam created a lake that extend back almost to Passu (Francis *et al.*, 1984). Earthquakes may play a role in triggering glacier surges directly or by means on rock avalanches which travel onto glaciers (DESIO 1954).

In the east side, various researchers observed and reported the retreating behavior of glaciers however, in the west, some researchers also reported the surging behavior of glaciers especially in central karakoram where large galciers has been expand and thickened including Shimshal, Hispar and Braldu glaciers (e.g. Bajracharya et al. 2007; Kayasthaand Harrison 200, Hewitt., 2005 and Immerzeel et al., 2009).In 2008, Pakistan Meteorological Department monitored the lake development on Hinarchi glacier and they found that lake originates as small pond but after three years the small pond develops into the big lake. The reasons behind this lake formation was considered the significant deposits of black corbon along with other contents of debris.

1.1.4. Earthquake induced Lake Formation

Glacier retreat is associated with many others types of natural hazards which are also interlinked including Earth-quakes induced ice loss, huge catastrophic flood and landslide/ slope movement, change in runoff regime and droughts (Richard son and Reynol ds 2000a, Cost a and Schuster 1988 and Harrison et al. 2006, Mark 2002). All these natural hazards are the main reasons for lakes formation in such a high mountainous areas.

The Hunza and Indus valleys of Northern Pakistan, deeply incised and seismically active (Shroder 1998), has a particular history of landslide-dammed lakes (Hewitt 1998) with specific cases in 1841, 1858, 1962, 1974 and 2010. The largest event is documented from the Indus valley near the Nanga Parbat. Several landslide-dammed lakes have formed in the last 50 years. Examples include the events of Aini (Tajikistan, 1964), Mayunmarca (Peru, 1974), Valpola (Italy, 1987), Tsatichu (Bhutan, 2003), Tangjiashan (China, 2008) and Attabad (Pakistan, 2010).

In terms of the amount of coseismic landslides and landslide dams, the Wenchuan earthquake ranks first among other earthquakes, such as the 1994 Northridge earthquake (Parise and Jibson, 2000), the 1999 Chi-Chi earthquake (Mw 7.6; Khazai and Sitar, 2004), the 2005 Kashmir earthquake in Pakistan (Mw 7.6; Sato et al., 2007) and the 2010 Haiti earthquake (Mw 7.0; Gorum et al., 2012).

1.1.5. Landslide dammed Lakes

It has been found that glaciated Northern regions of Pakistan is susceptible to natural hazards where all land is in the form ofrugged terrain including mountains and hills, harsh topographic condition and gravitative processes such as avalanches, landslides, debris flows and flash floods (Havenith et al. 2003; Passmore et al. 2008; Severskiy and Zichu 2000; Storm and Korup 2006; Yegorov 2007). Hough, (2007) reported that there are a number of active thrust faults and mega shear zones that pervade the Northern Pakistan. These faults are responsible for the high seismicity of the region. A number of significant earthquakes have been reported in during historic time. These include Gol-Ghone Landslide Dam (Hewitt, et al., 2011), which was seismically triggered along the Indus River, just downstream of its junction with the Shyok River.

The examples of manylandslide-dammed lakes has been found in Hunza and Indus valleys of UIB (Shroder 1998), with specific cases in different time periods like 1841, 1858, 1962, 1974 and 2010. The largest event is documented from the Indus valley near the Nanga Parbat. In the last 50 years, several landslide-dammed lakes have formed includingAini landslide (Tajikistan, 1964), Valpola (Italy, 1987), Tangjiashan (China, 2008),Tsatichu (Bhutan, 2003), Mayunmarca (Peru, 1974), and Attabad (Pakistan, 2010). Among the Earth-quake induced landslide events, theWenchuan earthquake is an utmost important events of the past. Besides that other widely known earthquakes includes Northridge earthquake (1994), Chi-Chi earthquake 1999 (Mw 7.6), Kashmir earthquake in Pakistan2005 (Mw 7.6; Sato et al., 2007) and the Haiti earthquake2010 (Mw 7.0); Gorum et al., 2012.

Due to the slopes and steep geographical conditions, great elevation differences, and fragile geological conditions these regions are vulnerable to landslide and river erosion (Gillani.S.N.A, 2013). After the passage of dam burst floods,landslides events have been reported at an increase rate in hunza valley (WRRI, NARC & UNDP 2008). During the last 100 years and before severalcatastrophic mudflows have been recorded (Gorbunov and Severskiy 2001; Blagoveshchenskiy and Yegorov 2009, Table 12.1). It has been shown that GLOF is responsible for about 11% of the catastrophic mudflows in this region.(Popov 1988; Medeuov and Nurlanov 1996; Medeuov et al. 1993, Yegorov 2007).

It has been found that recent and former landslide dammed lakes are widely spread in these regions. This area is well known due to its tectonic uplift, extremely rugged terrain as well as exhibiting the highest rates of denudation and channel incision in the world (Hewitt, 2009). Landslide dams lakes are of particular interest because majority of them are unstable and easily burst after their formation (Costa and Schuster, 1988). The formation of landslide-dammed lakes is often a highly significant secondary effect (Clague and Evans 1994; Casagli and Ermini 1999).

The examples of temporary landslide dams lakes have occurred along the upper Indus River. However the factors responsible for such type of landslide re not known yet some researchers have postulated that more intense monsoons are likely responsible for some of the mega landslides. On the other hand Evans *et al.*, (1998) reported that the rock slides, ice avalanche, debris avalanches or rock avalanches are the main reasons for glacial lakes formation in such a hummocky debris landforms (Heim, 1932; Abele, 1974; Hewitt, 1999, 2001). Therefore there exist a numerous remnants of historic landslide dams impounding lake, especially on both side of the Indus River and its principal tributaries (Kazmi and Jan, 1997, Ahmed et al., 2003). The main stem of the upper Indus River in northern Pakistan has been obstructed by a large number of mega landslide dams at various locations . In recent past, upper Indus basin is affected by many destructive landslide events (Ahmed and Rogers, 2013).

1.1.6. Rock avalanche and Lake Formation

Rock avalanches are extreme events during which a substantial amount of material moves in a very short time. There have been several major rock avalanches in the study area. Hewitt (1998) mapped the location of 25 events. For every 14 km of upper Indus River streams is deposited by well-known rock avalanches (Hewitt, 1998, 2009a; Shroder and Bishop, 1998; Korup et al., 2010).Korup*et al.,* 2010 found that there are also many short lived rock avalanche and glacial/moraine dams concentrated in the high relief zones of the western Himalayan syntaxes, along the Gilgit, Hunza, and Shyok Rivers. In the Chapursan Valley, the reasons for glacial lakes formation are rock slides as suggested byHewitt., 2001. Similarly the deposits in the Shigar River at the confluence of the Braldu and Basha Rivers, near Mungo, are the remains of a rock avalanche that spread across the valley from the southern slope above Tsago. It was assumed by many researchers that largest rockslide avalanches in this region was triggered by earth-quake of Magnitude 8+ (Keefer 1984; Feldl and Bilham 2006; Kumar et al. 2006). For example Satpara Rock avalanche was another seismically triggered rock avalanche dam that occurred in historic time and impounded the Deosai Plains.

1.1.7. River impounded lake

High rates of bedrock incision (up to 12mm/yr.) of the Indus River have been observed by several researchers (Korup, 1010; Hewitt, et al., 2011). Another landslide debris dam about 200 m high blocked the Indus River near Jaglot in Northern Pakistan for more than six months. The dam was breached catastrophically after filling for six months, sending an outbreak flood hundreds of kilometers downstream, causing significant damage. In the recent past Attabad (2010) and HattianBala (2005) rock avalanches impounded natural barriers across the major tributaries of Indus River in northern Pakistan. Both of these natural dams still existing and pose a significant threat to the low-lying areas downstream. In 2010, a massive landslide near Attabad village incised the Hunza River resulting in the creation of a 22-km-long lake in the upstream. Usually such lakes are short lived and occasionally sustain for more than a year but this time, it remains for more than 3 years. The lake is mainly filled by the snow and glacier melt of the numbers of valley glaciers including Ghulkin, Passu and Batura and the high-altitude mountain glaciers.

Another example of mudflow incised river incision from baltbarNallah has been reported in hunza basin where hunza river was blocked by a fan over 150m long and 80 to 100m high, which resulted into 12km long lake formation almost 18km south of Batura (Zhang, X. and Shifeng, W., 1980). Johnson (1988), discussed in detail the impacts generated by the development of smaller ice-marginal lakes in the Karakoram. In hunza valleyextensive lacustrine deposits fromGulmit to Batura section is considered as geo-morphological evidence in order to study the history of lakes. Keefer., (1984) reported thatstrong earthquakes are among the prime triggering factors of landslides which may block rivers, forming landslide dams. It was proved by an earthquake-triggered giant landslide (1841)which dammed the Indus river, impounding a lake with a maximum depth of about 150 m and a length of approx. 30 km (Shroder, 1998).

1.1.8. Glacier dammed lake

Another factor that is responsible for lakes formation in Karambar valley, are some glaciers like Karambar, Warghut, Chillinji, and Chateboi glaciers that blocked from time to time the main river in historical times (Iturrizaga,2004b). Similarly in the upper Shimshal valley, for the first time field observations was carried out by Visser-Hooft (1926) in order to monitor theVirjerab Lake development and disappearance. Another lake in shimshal valley was also analyzed which is formed due to the advancement of two glaciersthat temporarily blocked the main Shimshal valley, impounding runoff from Virjerab Glacier resulted in the accumulation of water which develop into lake. It was found that above mentioned Glacial lakes developed in remote mountainous areas which are difficult to access and field studies are laborious and cost-intensive. Therefore, remote sensing data and GIS are ideal tools for studying and monitoring glacial lakes and assessing their hazard potential (Buchroithner 1996; Huggel et al. 2003; Schneider 2004; Kääb et al. 2005; Quincey et al. 2005; Bolch et al. 2008).

MATERIALS & METHODS

The basic materials that were required for this study are high quality topographic maps, Historical Data, Lakes inventories, Digital Elevation Model (DEM) and Landsat Satellite imageries. For the identification of glacial lake, Google Earth and Landsatsatellite imageries were used. With the help of DEM (both ASTER &SRTM DEM) the elevation of the glacial lakes was derived. Further verification of glacial lake data was carried out by GE satellite images.The data was edited, managed and analyzed by using remote sensing and GIS software packages, such as Google Earth, Postgre/ Post GIS, and Python. Several glaciers and lakes are located in inaccessible mountainous areas which makes it difficult to monitored these lakes in the past but now a days different techniques like RS &GIS solve this problems by providing high revolutionary ground images (Quincey., 2005 &Bolch. et al., 2008).But in the glaciated UIB, different factors like cloud cover during the monsoon season and snow cover during winter pose hindrance in precise image interpretation. This problem was solved by using only those satellite images which is acquired during September– November in the Northern mountain range of Pakistan.

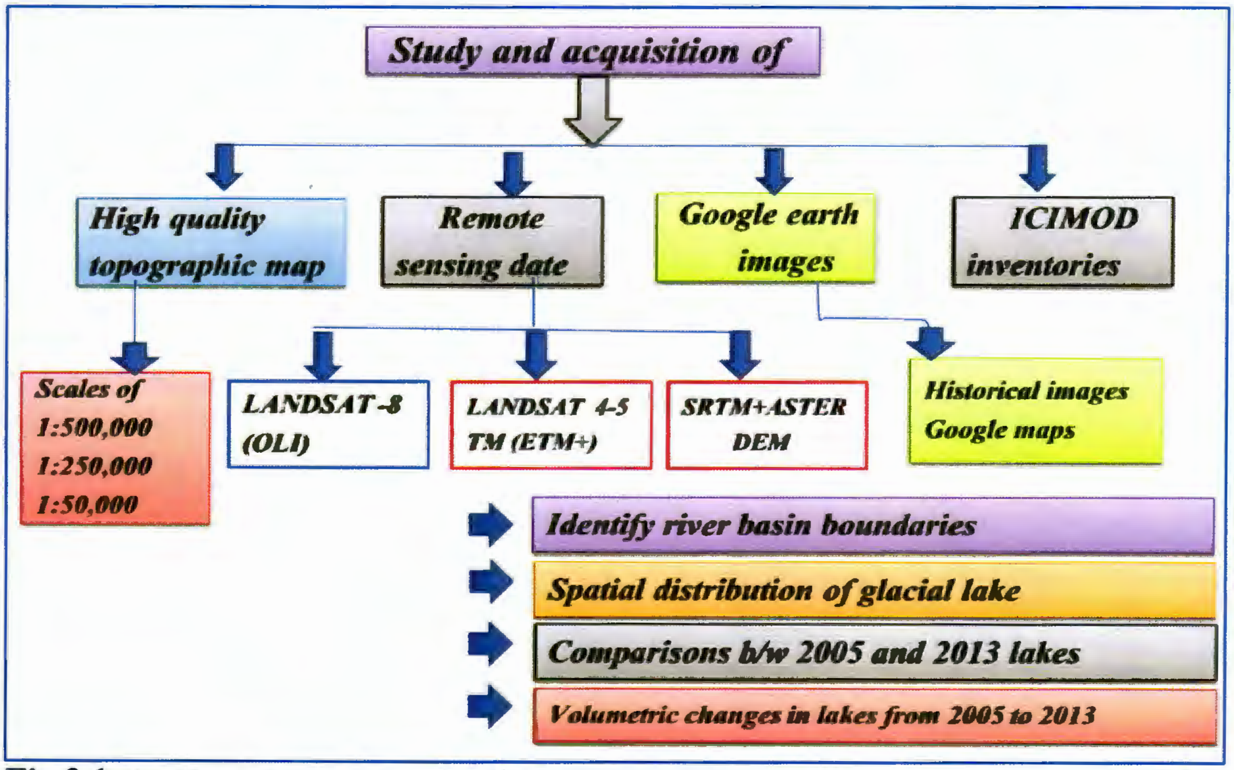


Fig.2.1: Detail set of materials and methods

2.1. Satellite imageries

In the present study, High-quality mulitemporal Landsat images from 2001 to 2013 were used as the primary source of information. The images with pixel size of 15m and 30m was downloaded from (http://glcf.umiacs.umd.edu and http://glovis.usgs.gov). The images were radiometrically correct and project in the UTM coordinate system. Pan-sharpened Landsat 7 scenes for the year of 2006, 2007, 2008, 2009 and 2010 while Landsat 2-3MSS/ 4-5TM scenes for the year of 2001, 2002 2003, 2004 and 2005 were used for the delineation of glacial lakes, identification of newly formed and disappeared lakes was carried out in glaciated ten sub basin. Glacial lakes were identified clearly in the band combinations of Pan, 7, 6b and 5, 4, 2 (Red, Green, Blue) due to their distinct true color and contrast with the surrounding features. In the false color composite of 5, 4, 3 (RGB), the water bodies, like lakes in blue color, was differentiated from the shadow areas appearing black in this band combination.High concentration of glacial lakes is found in north.

2.2. Topographic map

Further information of glacial lakes(river basin boundary and spatial distribution) was identified with the available topographic maps at scales of 1:500,000, 1:250,000 and 1:50,000. The digital topographic maps were (ARC digitized Raster Graphics (ADRG) published in January 1996 by the National Imagery and Mapping Agency (NIMA) and Defense Mapping Agency (DMA) of the U.S.

2.3. Glacial Lakes Inventories

The previous and current lakes inventories of Upper Indus Basin developed by ICIMOD in 2005 and 2013 were also used as a reference in present study.The present study was carried out in ten glaciated Indus sub basin of Pakistan.

2.4. Data collection and processing

In this study, the lakes inventories (2005 & 2013) developed by ICIMOD were used as reference data in order to identified those lakes which were appeared in 2013 inventory but absent in 2005 inventory, similarly also identified those lakes which were absent in 2013 inventory but present in 2005 inventory. By doing this we were able to identify which lakes were newly appeared and disappeared during the period of 2001- 2013. By comparing the inventories a total of 50 lakes were identified in ten sub Indus basin of Pakistan and results showed that out of which 45 lakes were newly appeared while 5 lakes were disappeared in 2013. After that we found out the factors which were responsible for the formation and disappearance of glacial lakes.

The database generation and spatial analysis was performed in GIS 10.1 software using the Transverse Mercator projection system. After getting all required data, it was processed by determining lake distribution in UIB and separation of lakes with area greater than200 sq.km while neglecting the supraglacial lakes because these lakes are unstable and continuously formed and disappeared. Gacial lake boundaries and its area were calculated by automatic method of water-pixel extraction and GIS software.Normalized difference water index (NDWI) of multispectral imagery was also computed in order to discriminate between water and other types of surface. Any other type of image misinterpretation due to shadow, lake· ice formation, cloud and snow cover features was eliminated by GE and DEM. The missing part of the lake boundaries from the ETM striping was manually corrected based on earlier TM or ETM images without striping. Cross-validation and modification for each glacial lake was conducted according to the time series areal variation. Details of the Landsat images used are shown in table 1.

Table 2.1: Data used in the study and corresponding application

Source/sensor	Date/year	Resolution/scale	Application
Topographic map	1970s	1:50000	lake identification
Landsat 2-3(MSS)	2001, 2002,2003	30m	lake identification
Landsat(4-5) TM	2003,2004,2005	30m	lake identification
Landsat 7 (ETM+)	2006,2007,2008	30m	lake identification
Landsat (OLI)	2013	30m	lake identification
Google Earth scenes	2001-2013	-- -	lake identification
DEM	1970s	30m	lake identification

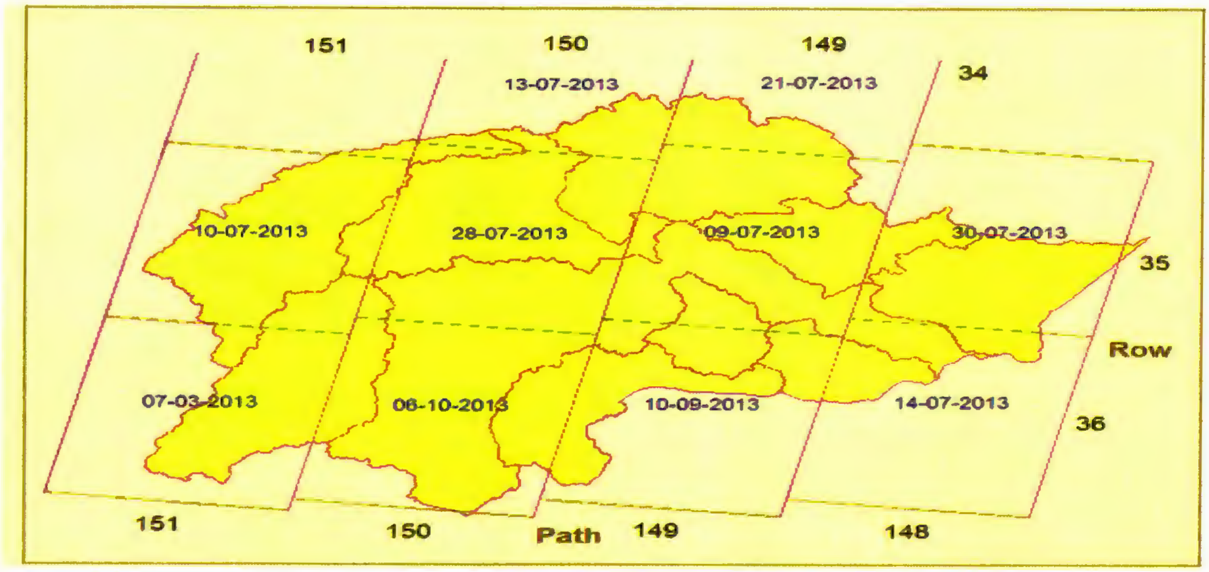


Fig. 2.2: Index map of Landsat images covering the HKH region of Pakistan

Detail information of row & path according to which satellite imageries are used are given below.

Table 2.2: Details of Landsat scenes (2001-2013)

Serial no	path	row	Bands	Spatial resolution	Years
1	148	35	Landsat (4-5),7 TM/ETM+,OLI	15m,30m,60m	2001-2013
2	148	36	Landsat (4-5),7 TM/ETM+,OLI	15m,30m,60m	2001-2013
3	149	35	Landsat (4-5),7 TM/ETM+,OLI	15m,30m,60m	2001-2013
4	149	36	Landsat (4-5),7 TM/ETM+,OLI	15m,30m,60m	2001-2013
5	150	34	Landsat (4-5),7 TM/ETM+,OLI	15m,30m,60m	2001-2013
6	150	35	Landsat (4-5),7 TM/ETM+,OLI	15m,30m,60m	2001-2013
7	150	36	Landsat (4-5),7 TM/ETM+,OLI	15m,30m,60m	2001-2013
8	151	34	Landsat (4-5),7 TM/ETM+,OLI	15m,30m,60m	2001-2013
9	151	35	Landsat (4-5),7 TM/ETM+,OLI	15m,30m,60m	2001-2013

RESULTS & DISCUSSION

The present study was conducted from September 2015 to August 2015 on causes of Glacial lakes Formation, Expansion and Disappearance in glaciated mountains of Northern Pakistan and its association with Climate Change. Fifty glacial lakes were selected from ten sub basin while meteorological data (Temperature & precipitation) were taken from Pakistan Meteorological Department(PMD).

3.1. Factors responsible for glacial lakes formation in study area

There are numbers of Factors which are responsible for glacial lakes formation in our study area. First of all here we discuss some examples of **seismic and tectonic factors**which results in lakes formation in glaciated regions of Northern Pakistan.

3.1.1.Earth quake induced landslide

There are a large numbers of earth quake induced catastrophic landslide dam events widely distributed in Northeren areas of Pakistan as it fall into world second dangerous zone(seismic zonation mapwww.munichre.com/en//ts/geo risk)with an expected intensity value of MMI scale VIII (Modified mercalli scale). Landslides are usually triggered by a combination of factors, such as intense and prolonged rainfall, rapid snow melting, earthquakes, and anthropogenic activities, such as excavations.

a. Jhelum basin; Hattian Bala landslide Lake (2005)

On October 8, 2005, a magnitude 7.6 earthquake struck Pakistan and caused many casualties as well as severe damage. Several mass movements were triggered. The Hattian Bala landslide southeast of Muzaffarabad (Fig.3.1)was reactivated, resulting in a rock avalanche with a volume of approx. 65 million m^3 (Dunning et al. 2007; Schneider 2009). An area of 1.8 km^2 was directly affected by the landslide, the deposit formed a dam with an area of 0.9 km^2 impounding Karli and Tung river and creating two lakesknown as zalzal Lake (major), which was 3.94 km long, and Bani Hafiz Lake (minor), about 1 km long(Fig.3.2**).**The largest one is**Zalzal lake** situataed near to Bani Hafiz Lake in 73° 43’ 9.133” E Longitude & 34 ° 7' 58.078" N Latitude with an estimated area of 327147 sq. km.The **Bani Hafiz lake** which is situated 73° 44' 19.265" E *longitude and 34° 8' 13.524" N with an estimated area of 58534 sq.km.Zalzal Lake, the larger of* the two, would grow to a volume of approx. 61.7 million m³, Bani Hafiz Lake to 3.6 million m³ **(Schneider 2009).Jhelum Lake # 200** is another lake which formed due to the secondary landslide near the toes of the Hattian Bala Landslide Dam were likely exacerbated by seepage through the slide debris.This earthquake made some geographical changes in the area, as result water can't drain and start to accumulate which develop into lake in 2010.This was observed from the reddish color of seepage emanating water at various locations downstream (Konagai and Sattar, 2011).

1.Zalzal lake # 198B (2006):

Fig. 3.1: Image **a** show the earthquake induced Hattian Bala landslide impounding lake, **b** indicate the vegetation cleared area due to debris flow which also block the riv shows the direction of rock avalanche and vegetation free area, ow the Karli river incision

2.Bani Hafiz lake # 199V: (2005)

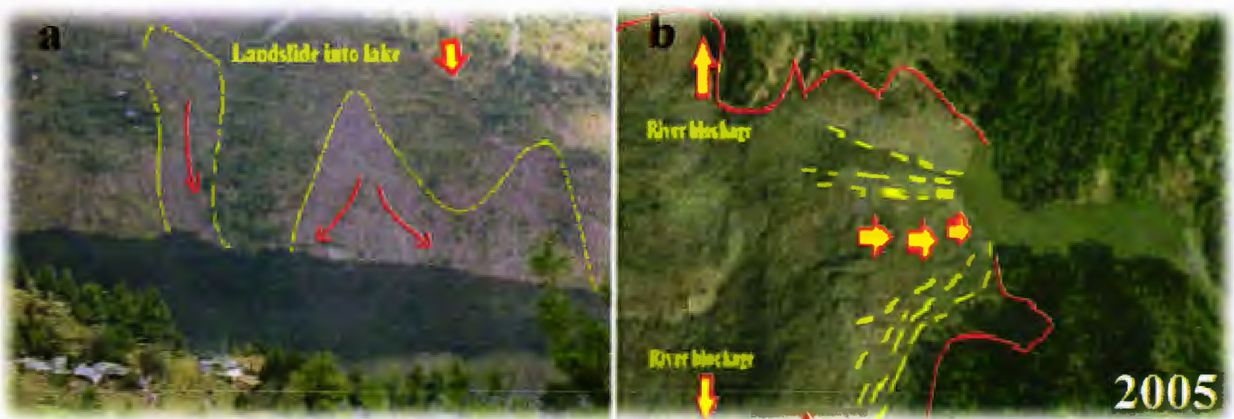


Fig.3.2:(a) indicate the landslide debris flow into the lake (b)s ows the direction of rock avalanche and vegetation free area, show the Karli river incision

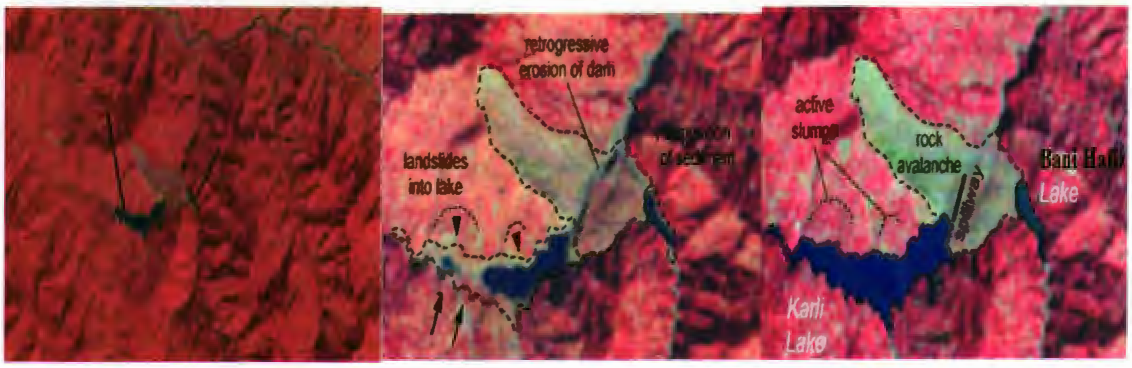


Fig.3.3:LANDSAT 7 ETM imagery with the sketch of landslide and rock avalanche which impound two lakes in Karli river.(www.wikipidia.com)

b. <u>Hunza basin:</u>Attabad Landslide Dam Lake # 13B (2010*)*

In January 2010 another earth quake struck Pakistan along the Hunza River, forming a landslide dam 120m high and impounding a reservoir more than 21km long near the village of Attabad (Figure 3.6) in the GilgitBaltistan area of northern Pakistan (Khattak, et al., 2010). This slide was structurally influenced by movement along a fault having a north-south strike, which crosses the Hunza River. The area has a history of seismically-triggered landslides as well as slides triggered by heavy rainfall, such as: the older Serat Rockslide, the Ghammessar slope failure (1858, 1962), and the Sulmanabadrockfalls (1991) (Shroder, 1998).

Fig. 3.4. Aerial view of Attabad Landslide Dam along the Hunza River in northern Pakistan. The lake surface partially freezes during the winter (www.googleimage.com)

c. **Astore basin:** Landslide dammed Dhirley Lake (2010)

The Dhirley lake # 175V is situated 74° 49' 38.665" E longitude & 35° 3' 10.128" N latitude in kalapani valley in betweenthe Rattu cant and Riat valley with an estimated area of about 313721 sq.km. This area hit by a huge catastrophic landslide in 2010 which dammed the Rattu River and form a lake.

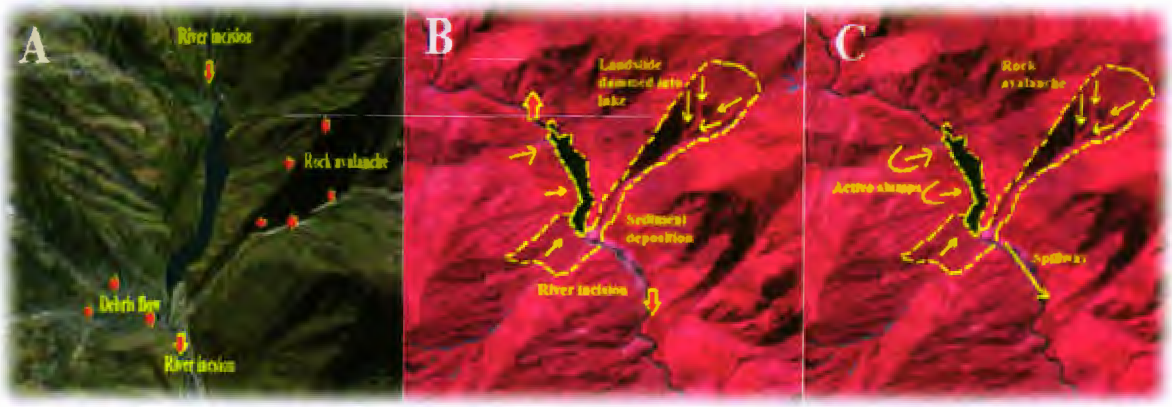


Fig.3.5: A Landslide dammed lake. **B & C** LANDSAT 4-5TMimagery with sketch of rock avalanche impounding lake

Image interpretation shows that rock avalanche bring debris and sediment depositions near the river which block the river flow completely and develop into a lake.

Fig.3.6: Panaramio view of Dhirleylake in kalapani valley.

d. Shyok baisn: Gayari landslide dammed Lake #85 (2012):

On 7 April 2012, a massive ice avalanche struck a Pakistani military headquarters at Gayari, 30 km west of the Siachen Glacier terminus, near the disputed Siachen glacier region. This landslide avalanche blocked the water and develops into lake with an estimated area of about 123909 Sq.km. But there are many speculations about this incident as a retired Pakistani Colonel Sher Khan said that the disaster was likely a landslide caused by heavy precipitation, not an avalanche. According to the PMD data ice is melting at the terminus of the Siachen Glacier and suggested that large carbon deposits from Indian military activity led to increased solar radiation as one of the prime causes of the incident. The avalanche site is 15 km west of any part of the Siachen basin, near the Gayari (Ghyari) River just below the Bilafond Glacier

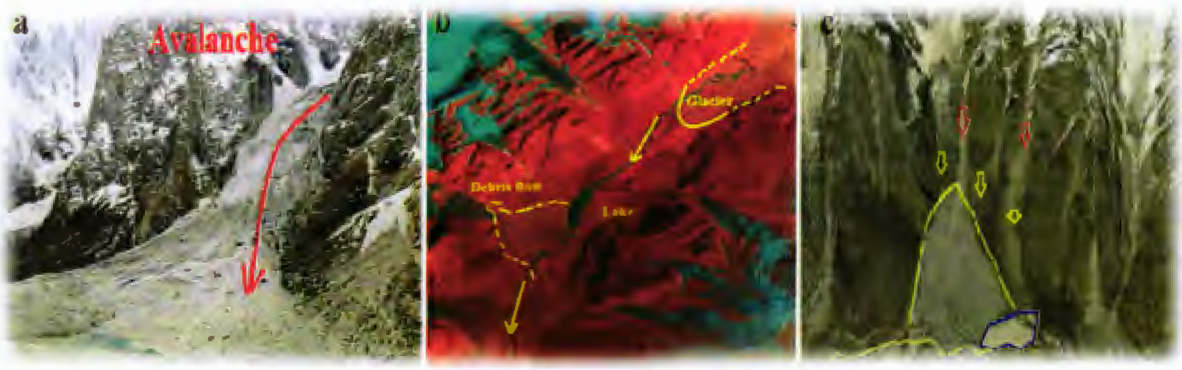


Fig.3.7:a iceavalanche during Gyari incident. **b** sketch of lake formation after landslide. **c** landslide dammed lake near Bilafono glacier.

Fig.3.8: Google Earth image of Lake formation after gyari incident 7-4-12

e. <u>Indus basin:</u> Landslide dammed Lake#612 E (2003):

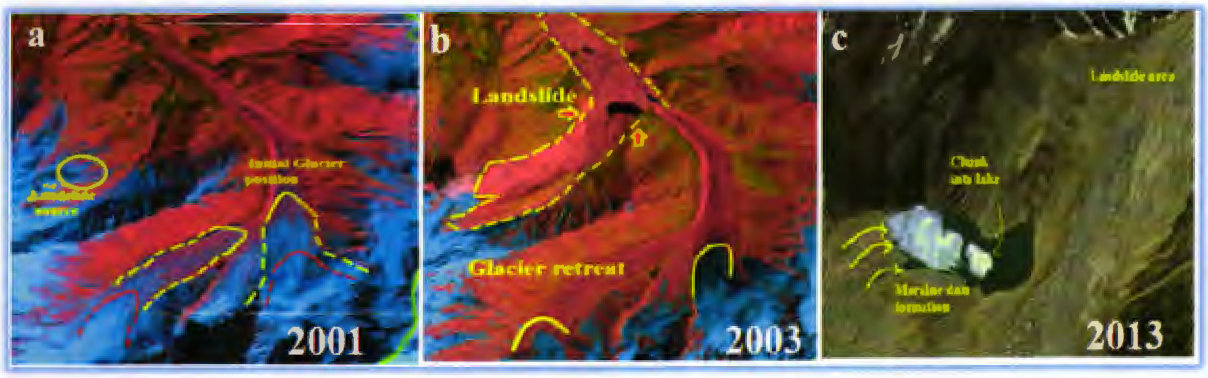
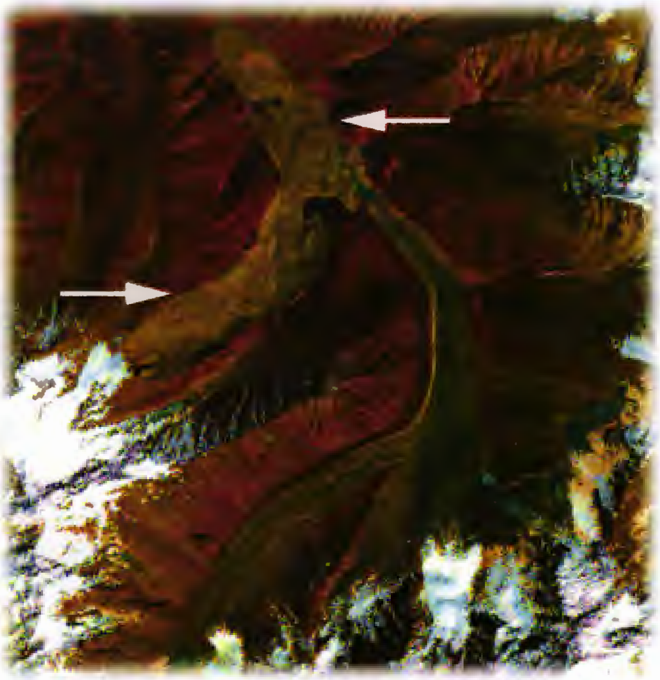


Fig.3.9: The Indus lake # 612 (~2.9km^2) has recently appeared in 2003 and is the result of a landslide that has covered the terminus of Buldar Glacier and blocked the Buldar Basin valley. Large sediment deposition are present at glacier terminus that impound a lake as shown in above image part c.



Buldar Glacier has surged in the past (Hewitt 1988), although it has retreated ~180 m. The terminus is also down wasting, whereas surge lobes, flow loops, and complex ice fracture patterns clearly document its chaotic behavior. Buldar Glacier on the north side of Nanga Parbat is a compound valley glacier that is avalanche fed. Its area in 1934 was 19.3 km^2 versus 17.7 km^2 in 2004. The change is due to significant terminus retreat, and the retreat/disappearance of a large tributary glacier that originated from Buldar Ridge, and flowed into the westernmost tributary glacier of Buldar Basin.

Fig.3.10. ASTER (bands 3, 2, 1, RGB) false-color composite of Buldar Glacier on the north side of NangaParbat. A large landslide (arrows) has blocked the Buldar Valley floor, thereby altering glacier meltwater flow.

f. <u>Indus basin</u>: Landslide dammed Lake #1V (2010):

Another example of landslide dammed lake in Indus basin is the Lake situated in Indus basin near Ranyal in 72° 48' 19.032" E Longitude &34° 54' 2.613" N Latitude with an estimated area of 44266 sq. Km. The reasons of lake formation is thought to be a landslide 2010 as it is interpreted through images that in this area a huge debris flow & rock avalanche occurred after landslide which blocked the indus river near Ranyal and lake is formed.

Fig. 3.11:A Landslide dammed lake **B** LANDSAT 7 ETMimagery with sketch map of rock avalanche impounding lake

g. Chitral basin: Landslide dammedLake # 86M (2002):

This chitral lake is formed by the combination of 2 events as shown in the image, In the earlier stages the Matkash glacier show surging behavior while parallel chonuk glacier also advance at that time finally both glacier meet at the point but later on due to climate change both glaciers start retreating and leaving behind a melting water which is dammed by landslide occurred in 2002 as a result lake is formed.

Fig.3.12: (a) Lake Formation events. Yellow Dotted lines indicate the matkash glacier surge while red dotted lines show the chonuk glacier terminus **(b)**landslide dammed lake in chitral

3.1.2. Glacier retreat/ Surge and lake formation

a. (Gilgit basin:Liligo Lake) & (Astore basin: Latobo Lake)

Liligo Glacier serves as a classic example, where its terminus has reached Baltoro Glacier and produced a large ephemeral proglacial lake that periodically drains. In later period of time Liligo glacier start retreating and leaving behind a cavity that filled with melt water and developed into a proglacial lake in front of liligo glacier in 2012.Similarly a proglacial lake associated with Tap Glacier on the south side of Nanga Parbat has also developed and increased in size to ~0.8km^{2}.

Fig.3.13:ASTER (bands 3, 2, 1, RGB)false-color composite of Liligo glacier with their surging behavior. (www.googleimage.com)

Fig.3.14. Liligo Glacier with proglacial lake on the south side of Baltoro Glacier (to the right).Liligo is a surging glacier and light-colored trimlines document the redistribution of ice mass.

Fig.3.15: Tap Glacier with moraine-dammed lake (left foreground) on the south side of Nanga Parbat.The debris-covered termini of Shigiri andRupal Glaciers are located farther up the Rupal Valley.

b. Gilgit lake:612M:

In Yasin valley, a Ghamu Bar glacier also retreat some km behind its original position leaving a cavity at its terminus position which later on filled with melt water and developed into a moraine dammed lake called as Darkot lake(~179451) located 73° 24' 23.014" E longitude and 36° 38' 33.021" Nlatitude.Lake area also increased from 2001 -2010.

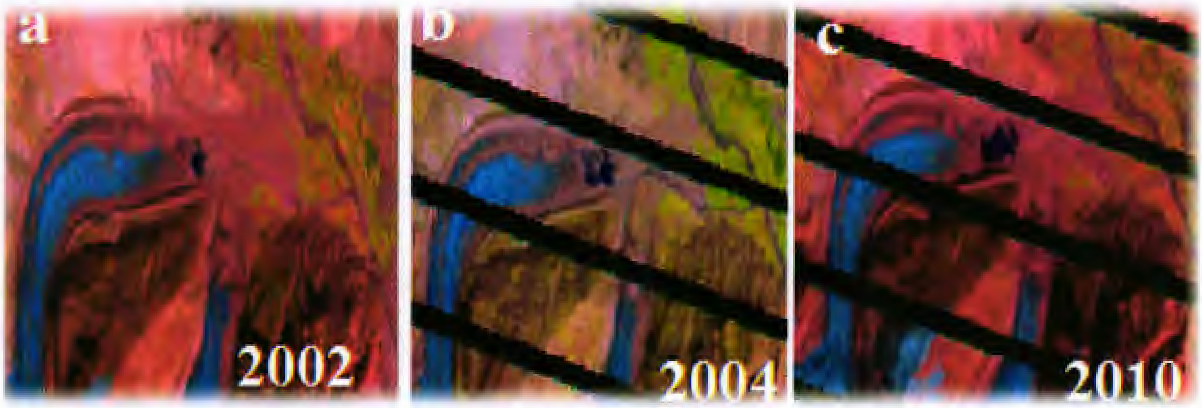


Fig.3.16: LANSAT 4-5TM(5.4.3RGB) False color composite of Ghamu bar glacier associated lake with their area expansion

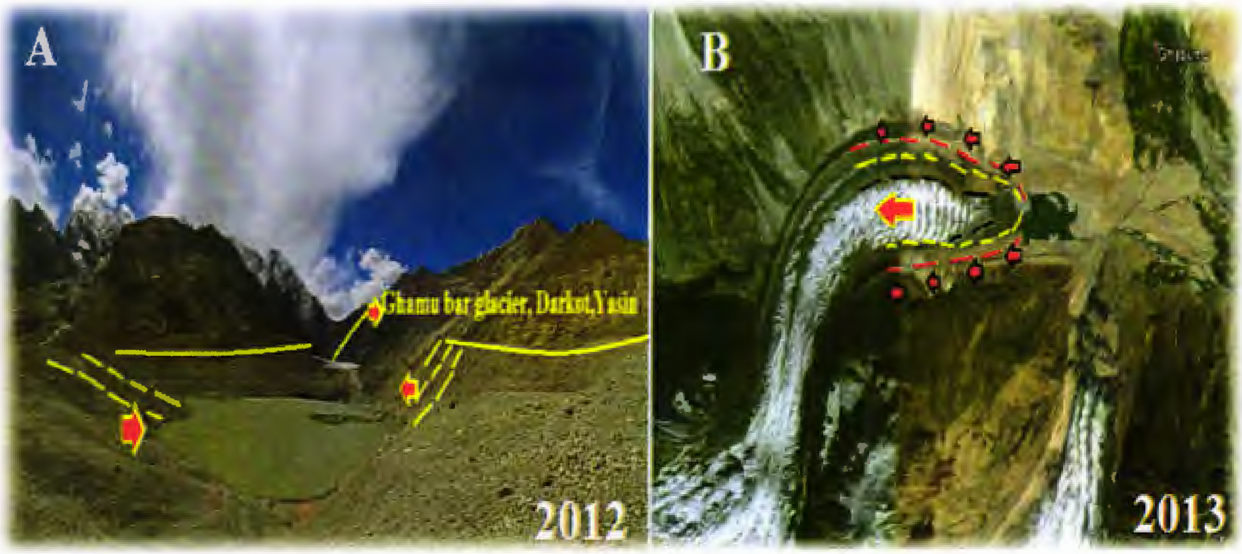


Fig.3.17:Ghamu bar Glacier with proglacial lake on the south side of kharegalGlacier (to the right).

c.Chitral basin: Lake#82M & 85M

In chitral basin, the ponarilio glacier near Yarkhunriver has retreated as a result a lake developed at its terminus. Similarly, in historical times Chianter glacier advance and reached to the Yarkhun valley after that it retreat resulted in the formation of moraine dammed lake at its terminus.

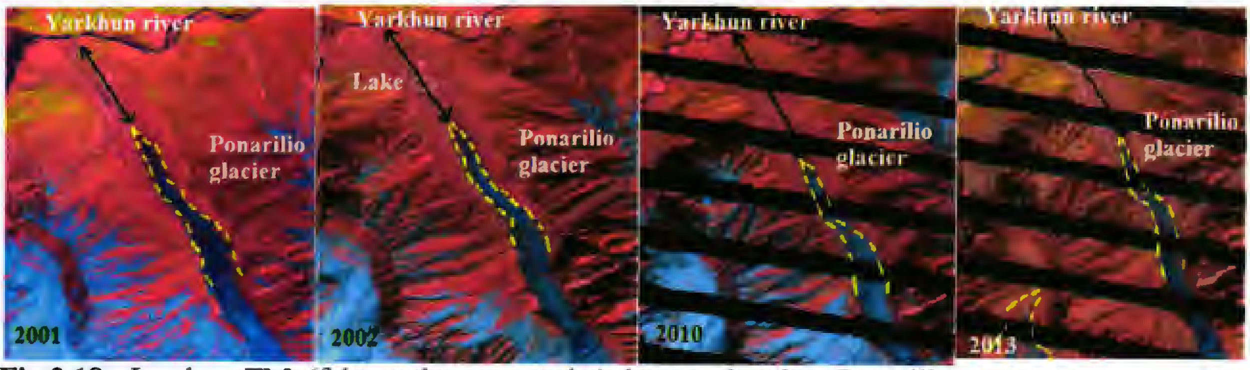


Fig.3.18: Landsat TM (false color composite) image showing Ponarilio glacier retreat and moraine dammed lakeformation

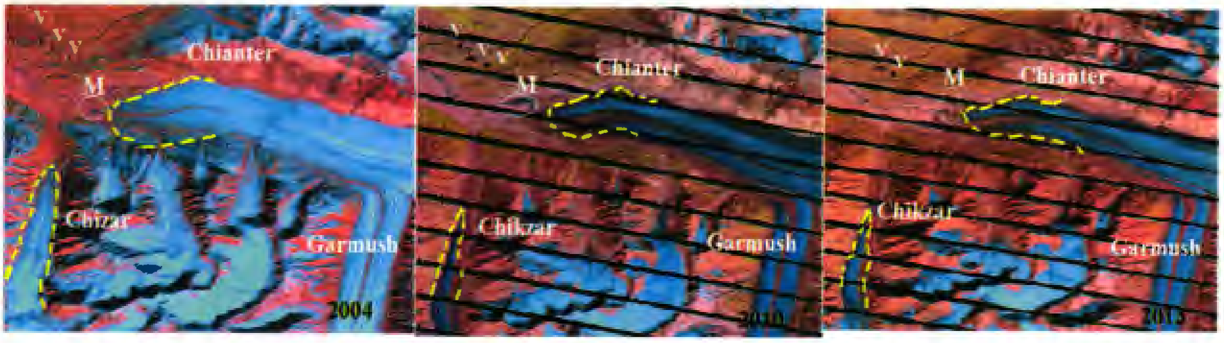


Fig.3.19: Landsat TM (5.4.3RGB) false color composite image showing Chianter glacier retreat and moraine dammed lake formation

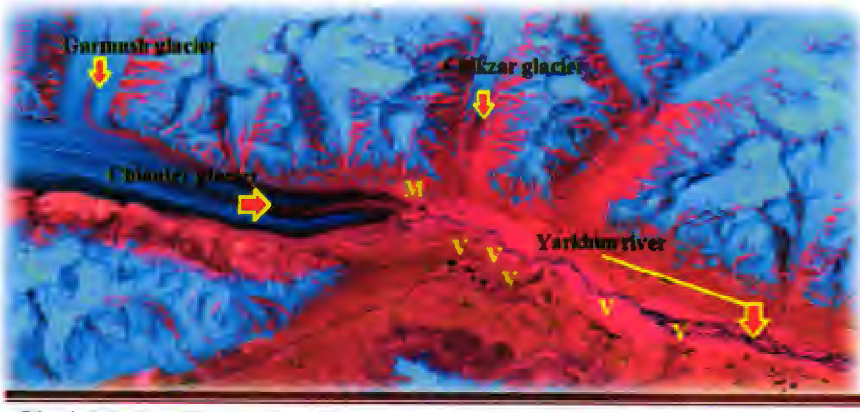


Fig.3.20: Chianter glacier with moraine dammed lake at terminus and numerous valley lakes along Yarkhun River.

d. Astore lake #160M:

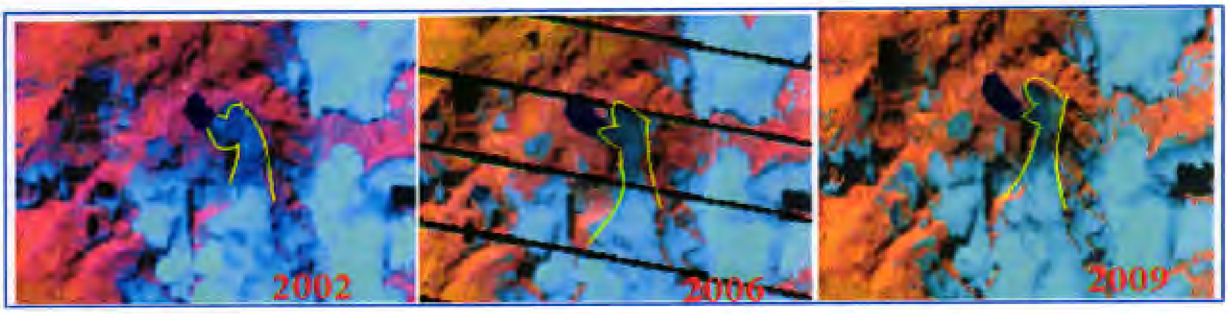


Fig.3.21: Temporal development and area expansion of lake 160M

The Astorelake located at glacier terminus in the latitude and longitude of 34.907754 & 74.681453.While chitral lake is located in the location of 36.180924 and 71.799405 Latitude and longitude. The image interpretation show the increase in the size of lakes with slightly decrease the glacier terminus leaving a space for lake water to accumulate.The areal extent of the lakes is also mapped from temporal satellite data from 2002&03, 2005 &06 and 2009&10.Astorelakeshow their areaincreaseof 0.25 $km^2$from 2002 to 2009.The satellite imageries shows that the both lakes is still attached to the snout but expanding laterally and is increasing in areal extent .

Fig. 3.22: Moraine dammed lakes at glacier terminus

e. Chitral Lake # 26:

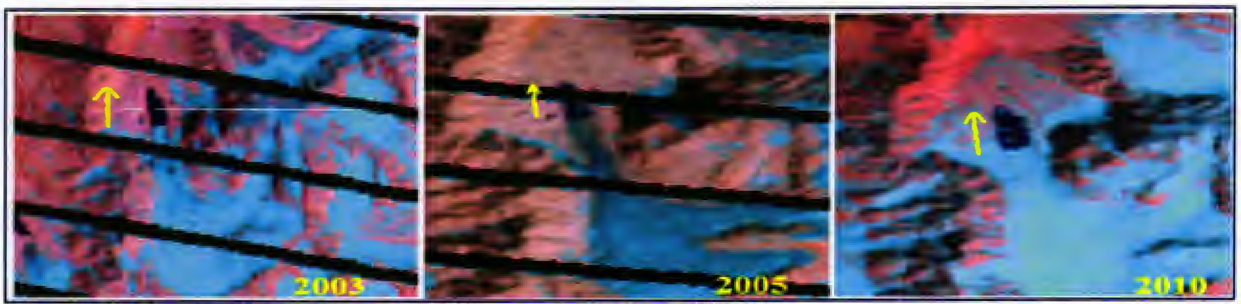


Fig. 3.23: Temporal development and area expansion of lake

f. Astore Lake# 98:

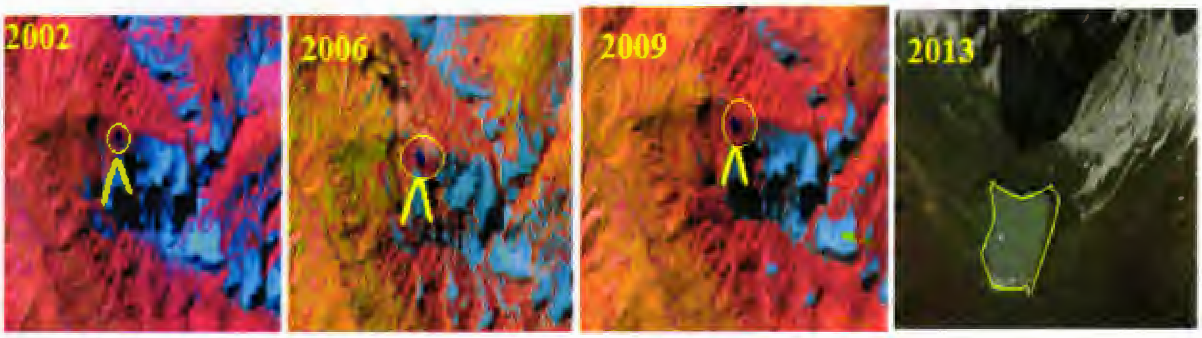


Fig.3.24:Temporal development and area expansion of lake 98M

Both Astore and chitral lakes are appeared at glacier terminus due to accumulation of melt water after glacier retreat in 2002 & 2005 respectively. The areal extent of the lakes is also mapped from temporal satellite data from 2002, 2005 &06 and 2009 &10. 2010 satellite image of chitral shows that lake is still attached to the snout but expanding laterally and is increasing in areal extent.

Fig:3.25: Moraine dammed lakes at terminus position of retreated glacier

g. Chitral lake#11

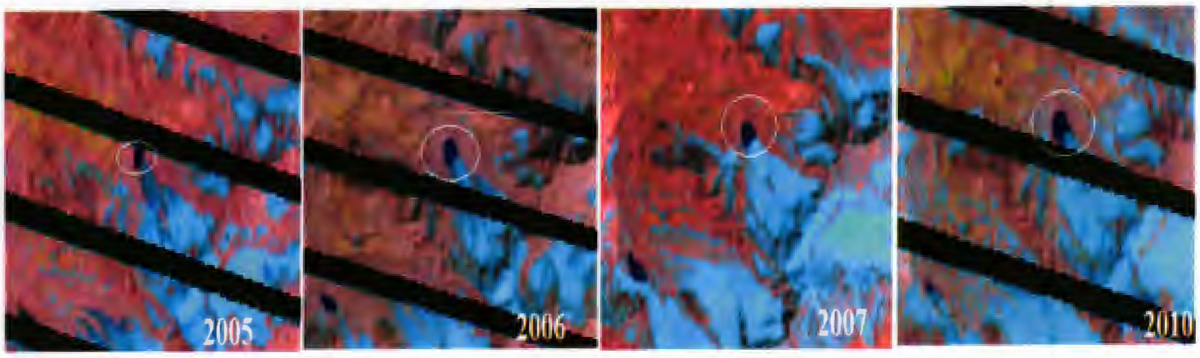


Fig.3.26: Temporal development and area expansion of lake

h.Indus Lake 608:M

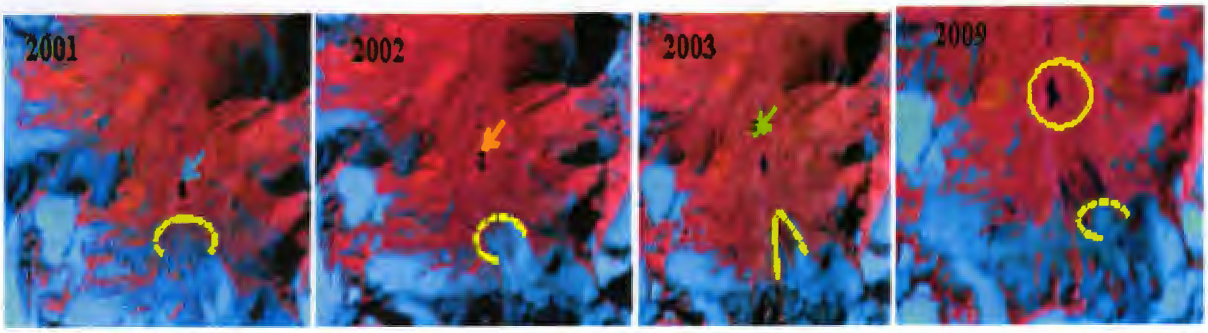


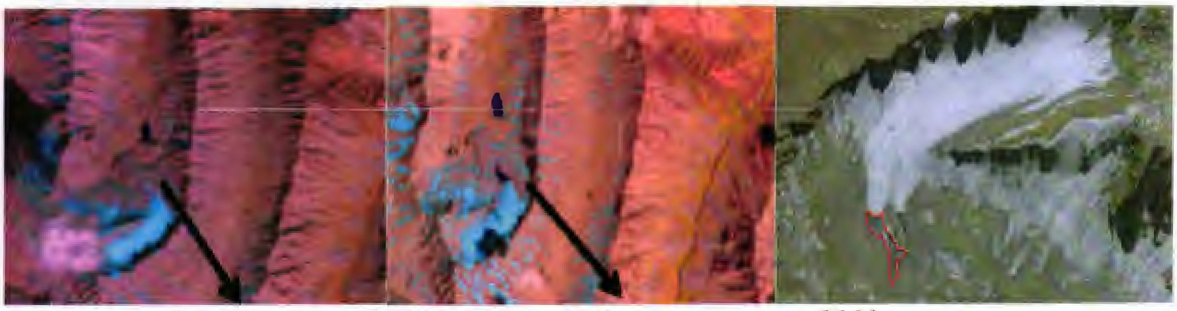
Fig.3.27: Temporal development and area expansion of lake

The change detection study revealed the glacier retreated 451 m during the 9-year period (2001–2009).Figure 3 shows the retreating ofglacierswith expansion of glacial lakes at different time periods.

i. Shingo and Indus lakes: M

Fig. 3.28: Moraine dammed lakes developed at terminus of retreating glacier

j. Shingo lake # 5



2001 **no lake** 2006 **(develop)** 2009

Fig.3.29: Satellite image of moraine dammed lake at glacier terminus

k. Gilgit lake#598M:

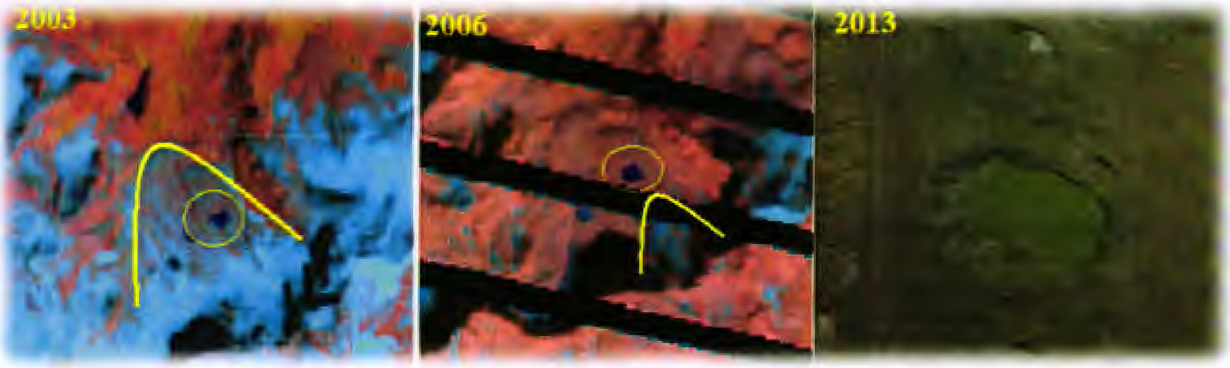


Fig. 3.30: Temporal development and area expansion of lake

l. Astore lake#29

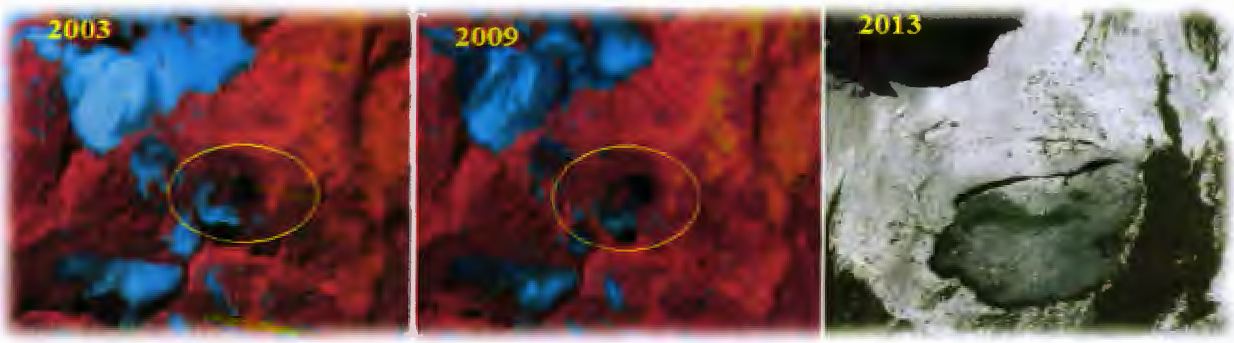


Fig. 3.31: Temporal development and area expansion of lake

m. Indus Lake 560M:

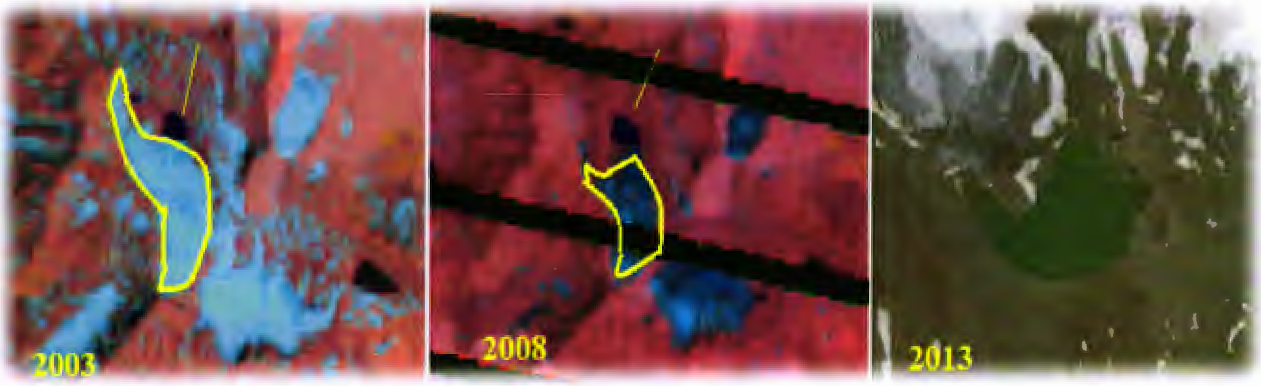


Fig. 3.32: Temporal development and area expansion of lake

3.1.3. River dammed lake

When a landslide spills into a river channel, or sometimes glaciers show surging/advancing behavior that often blocked or substantially retarded the river flow, and sediment begins to fall out of suspension in the upper reaches of the newly formed reservoir.

a. Gilgit Lake 638:

The Karambar valley, in which the Karambar, Warghut, Chillinji, SoktherRabot and Chateboi glaciers blocked from time to time the main river and reached to the Pekin glacier in historical times. With the passage of time glacier start retreating and leaving a space for river flow which later on blocked by huge debris flow and sediment deposition after a landslide incident.

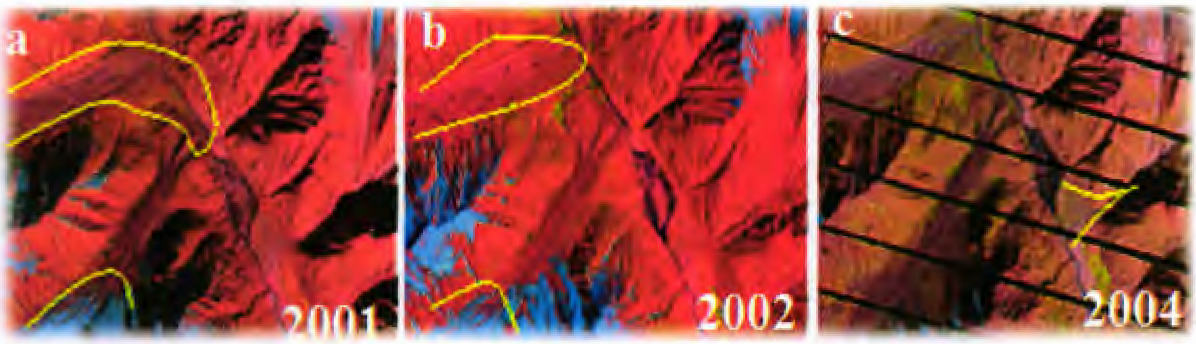


Fig.3.33: LANDSAT TM(5.4.3) false color composite of karambar glacier & lake

Fig.3.34: Karambar glacier with Valley Lake near the Pekin glacier

b. Chilinji glacier block karambar valley:

At some distance Karamber valley also blocked by another glacier named Chilinji glacier as a result glacier dammed lake is formed.

Fig.3.35: Karambar valley with Valley Lake near the Chilinji glacier

c. Shyok basin:Lake#33 V

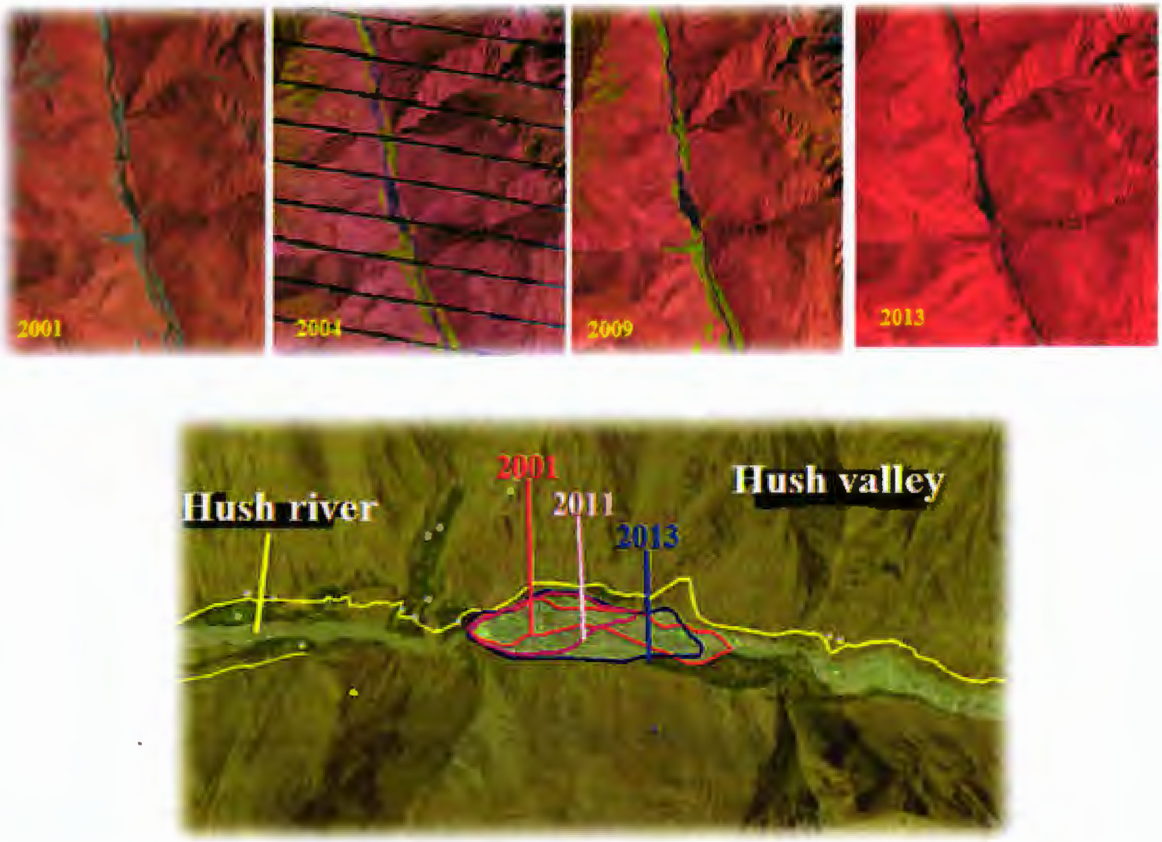


Fig. 3.36: Hush river impounded lake with area expansion in Hush valley

d. Hunza basin:lake#7V:

Naltar valley in hunza basin is effected by many landslide in different time perioud. Image interpretation show the sign of sediment deposition along the wall of valley at different position that blocked the naltar river which flow through the valley as a result various lakes are formed in this valley.

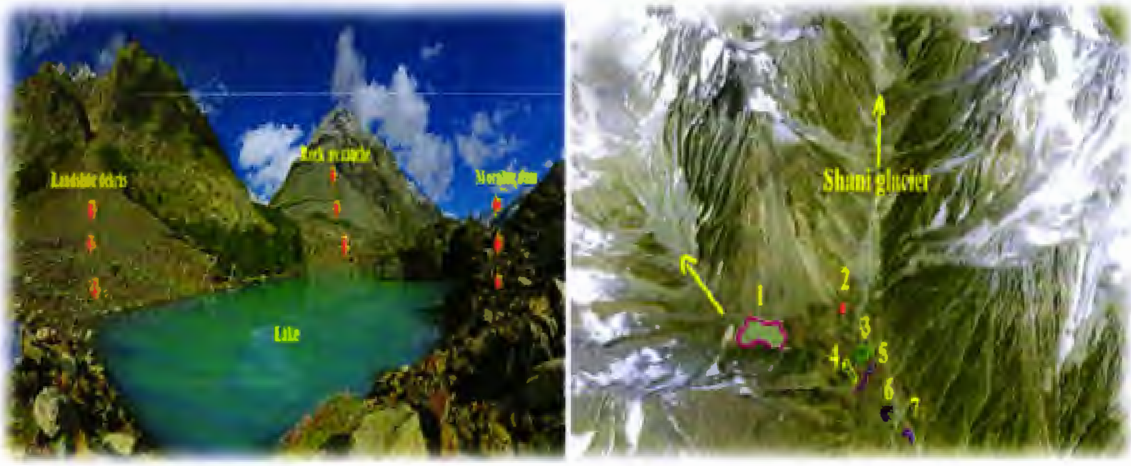


Fig.3.37: naltar valley alongwith numerous lakes

Fig. 3.38: Naltar valley with landslide and sediment deposition along naltar river.Show the landslide at different position and moraine deposits that blocked the river.

3.1.4. Glacier dammed lake

a.Hunza lake#157:L

In Shimshal valley, the Yazghil glacier terminates at an height of 3150 m. The separated glacier tongue creates two main potential dams. The bifurcation of the glacier tongue might be caused by the rock bar lying in the middle of the Shimshal valley floor. The western tongue is located in a distance of about 150 m from the other valley side, the eastern tongue only 20–30 m. In historical times the glacier reached the river. The lateral moraine of glacier lose its height and demolished where melteater accumulate and developed into lake.

Fig. 3.39: View from 3850m towards the upper catchment area of the white Yazghil glacier (left) and onto its tongue end at 3150m. The separated glacierterminus creates two potential dams .

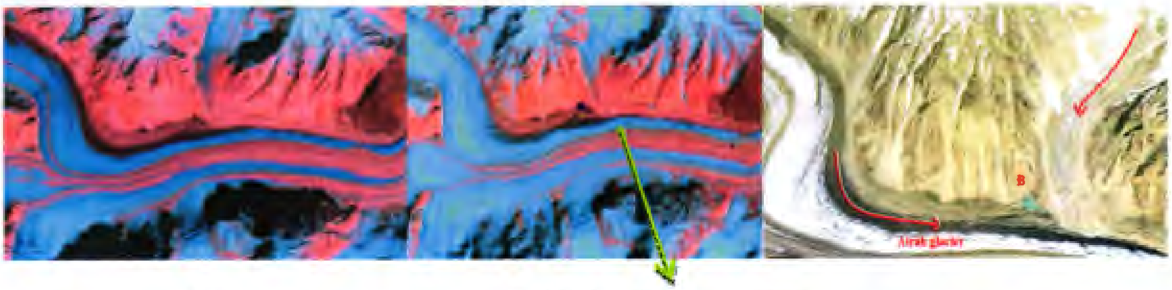
Fig.3.40: Yazghil glacier demolishes its lateral moraine at 3,650 m. Photo: new lateral moraine is formed. Photo: Iturrizaga.

b. Shigar basin:Lake# 99&100 B

Fig. 3.41: Similerly an unknown glacier in shigar basin advance along its tributry which blocked the meltwater flow and resulted in lakes formation.

Fig. 3.42: Atrackglacier in Chitral basin advance along its tributry which blocked the meltwater flow and resulted in lakes formation

c. Chitral LAKE#33:B



2001 2003(**develoop**) 2013

Shyok lake#104& 122:B

Fig.3.43: Google earth image show the blocked lakes

3.2. Area Expansion Lakes

Shyok 106L & Hunza 157L :

Fig.3.44: Lakes with area expansion

Astore Lake#171:

Fig.3.45: Lakes with area expansion

Gilgit 9M& Shyok 149B lakes:

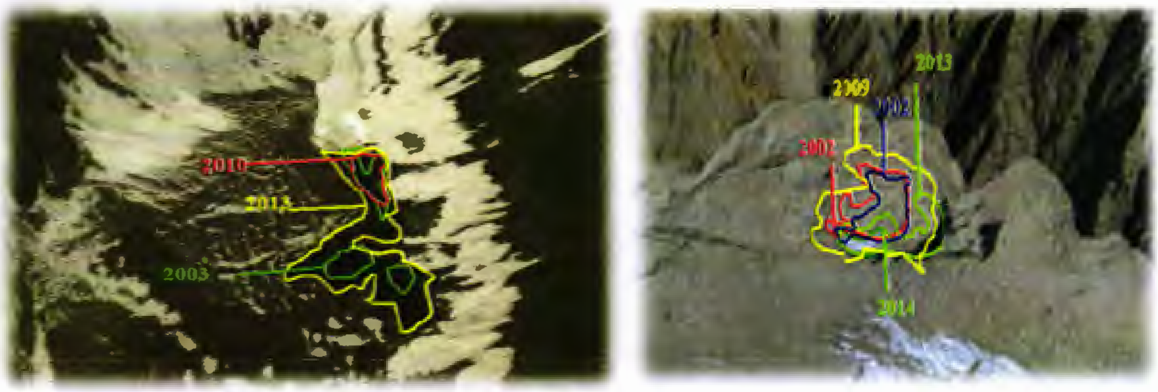


Fig.3.46: Lakes with area expansion

Zalzal & Bani Hafiz Lakes expansion:

Fig.3.47: glacial lakes with their area expansion.**(a)** show that area increased from 2005 -2010 but it decreased in 2012. **(b)** show contionous increased in area from 2005- 2010

Both lakes show their area expansion after their formation from 2005 to 2010 thereafter they start breaching in July-August 2010 which result in huge catastrophic Flood, as a result the reservoir stage lowered by 15m.

i.Astore lake # 51 M:

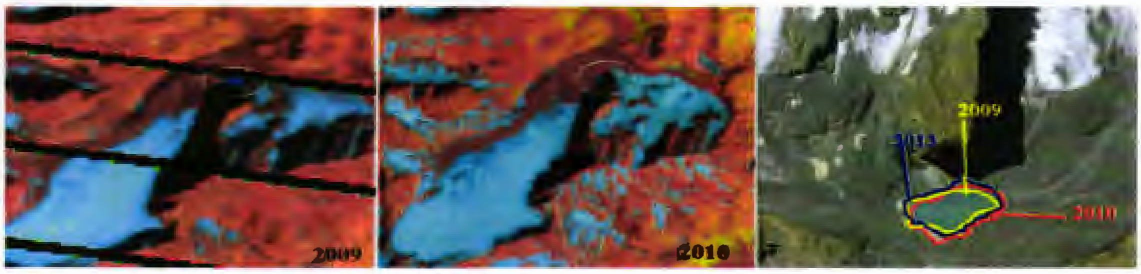


Fig.3.48: Temporal development and area expansion of lake

Astore Lake 11:

Fig. 3.49: Temporal development and area expansion of lake

3.3. *Disappeared lakes*

Shingo lake#15:

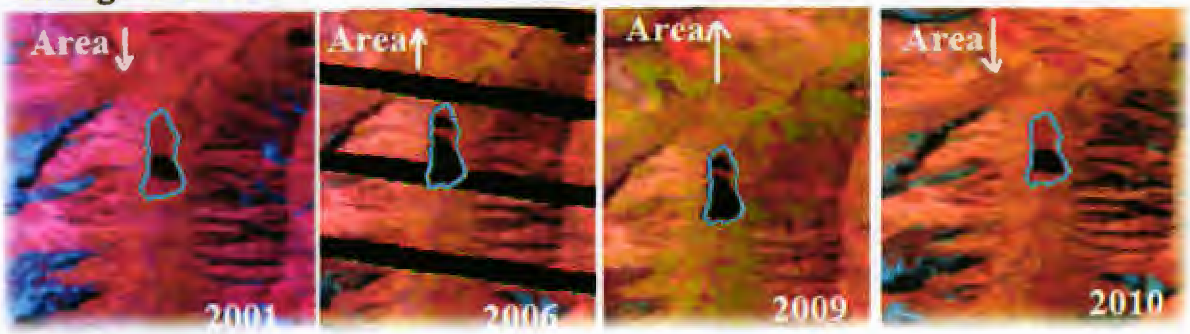


Fig.3.50:continous decrease in the area of glacial lake

Shyok lake 106:

Fig.3.51 : Lake present in 2009 but disappeared in 2014

Indus lake 21b:

Fig.3.52:continous decrease in the area of glacial lake

Shyok basin: unknown lake on siachen glacier

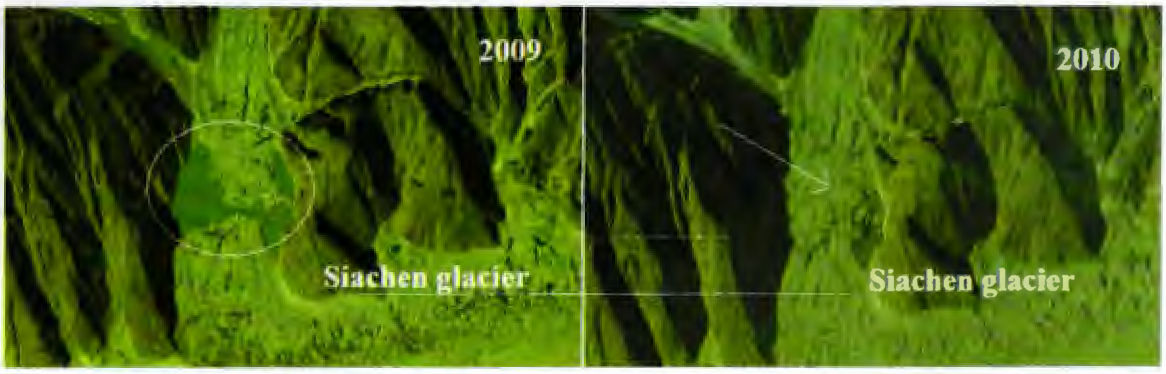


Fig.3.53: Google earth image show lake present in 2009 but disappeared in 2010

Shigar 94 B:

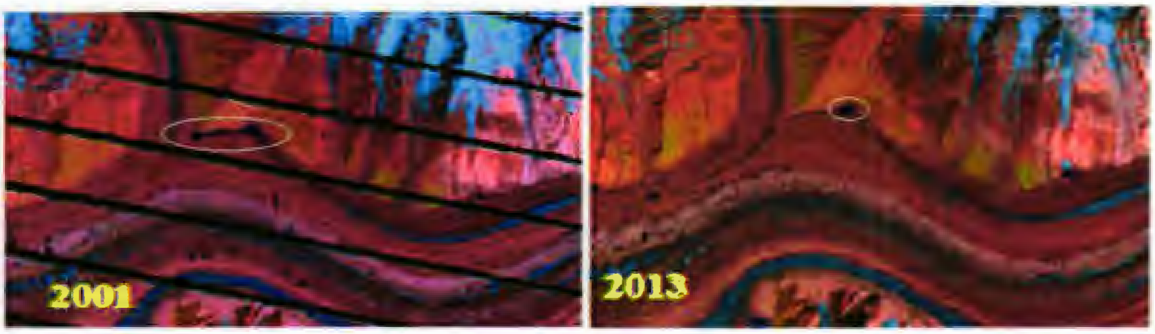


Fig.3.54: Satellite image show decrease in the area of glacial lake from 2001-2013

Gilgit lake#536 V

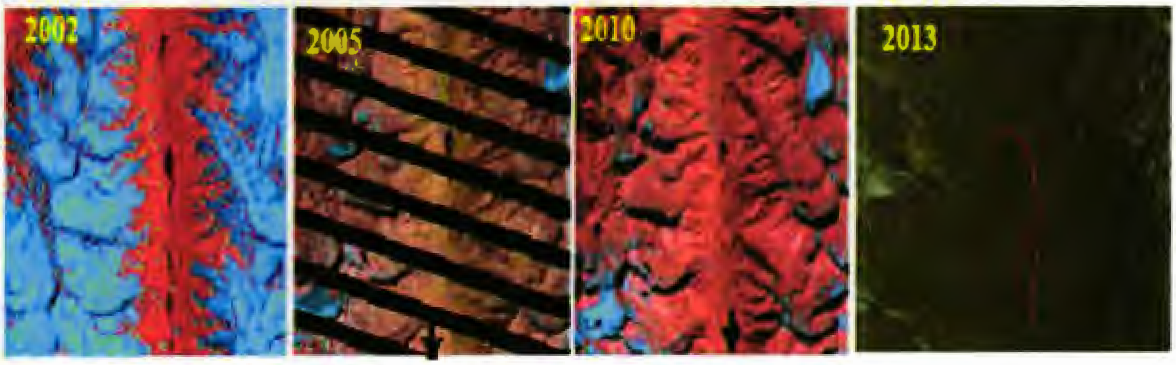
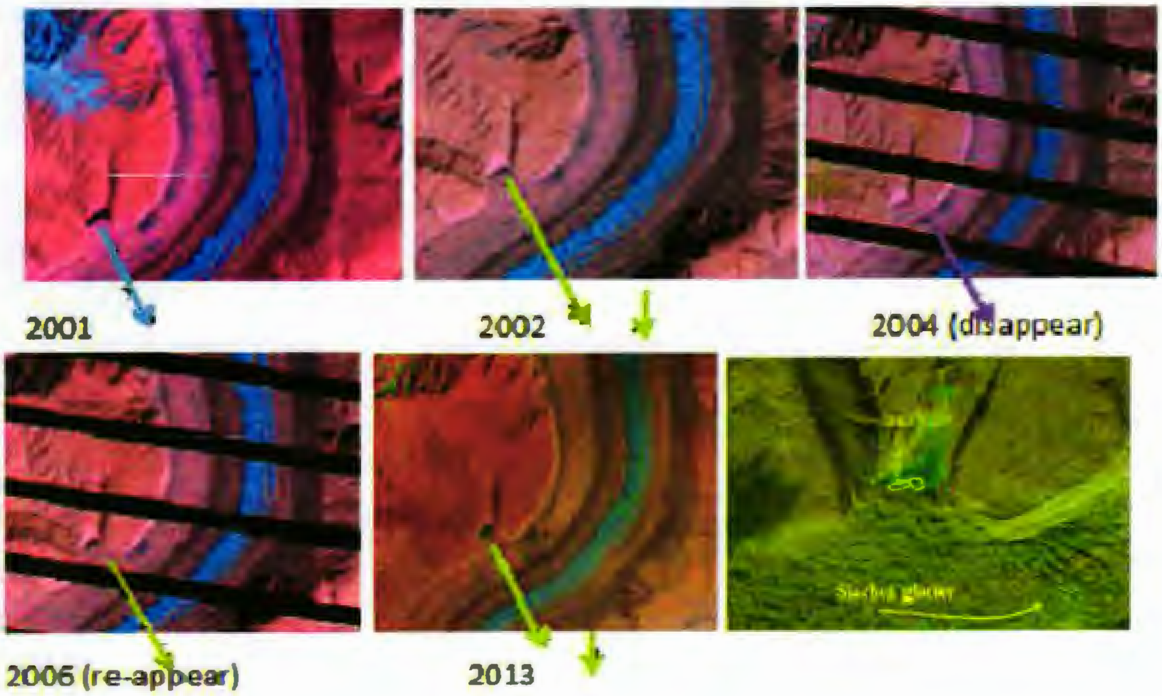


Fig.3.55: Continous decrease in the area of glacial lake

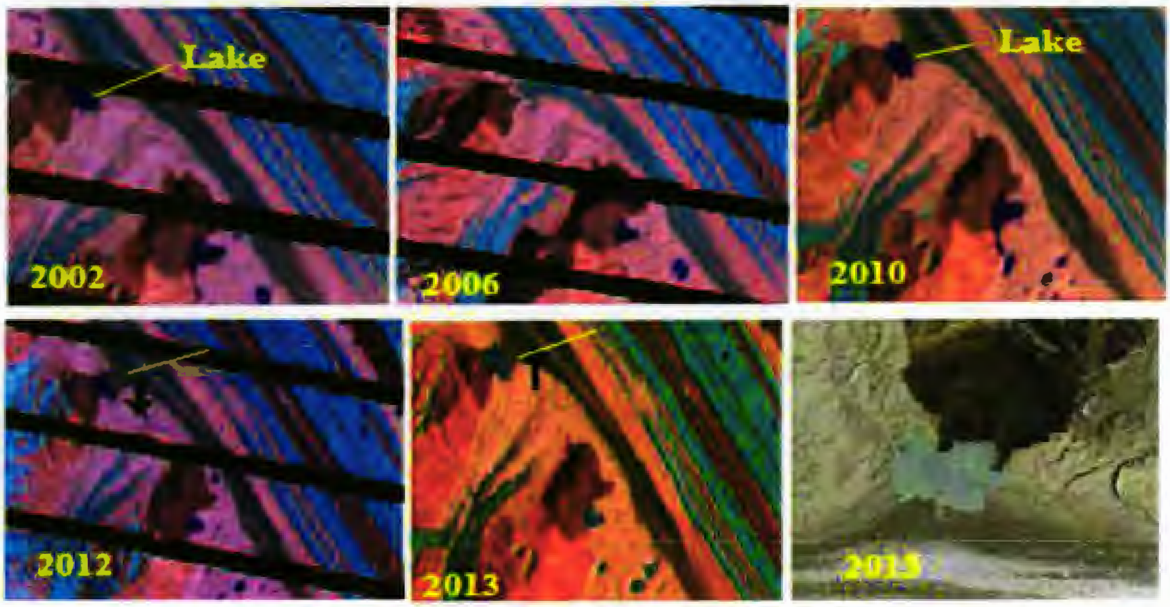
3.4. Breach and refill lakes

Some lakes in glaciated UIB also show the breach and refill characteristics.

Shyok lake # 104:L

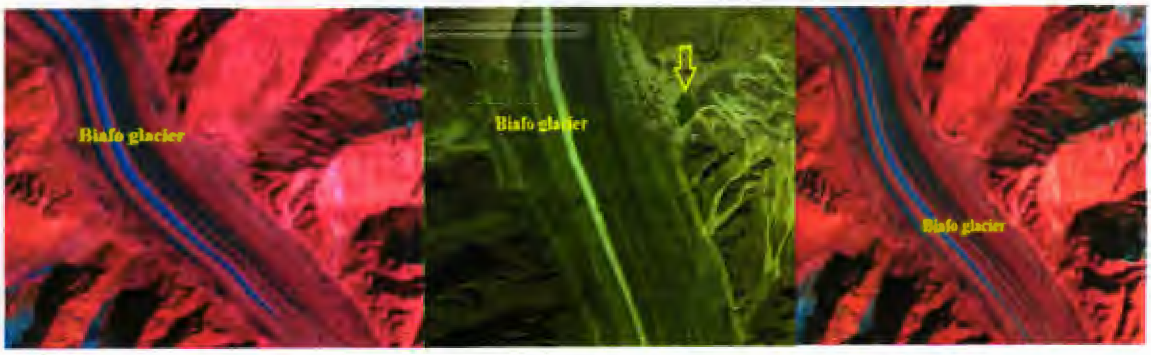


Shyok lake#122;B



Shigar basin unknown lake:L

Shigar basin:unknown lake:



2001 2006(develop) 2007 (breach)

2014 (reappear/refill) 2015(area increase)

Results showed that about 60 % hazards faced by the remote communities in glaciated mountains of Northern Pakistan are associated with Earthquake and glacier surging. The hazards like floods, river erosion, rock avalanches, landslides, etc. are interlinked, i.e., intensity of flash floods may increase the process of river erosion and in cases cause triggering of landslides and rock avalanches.

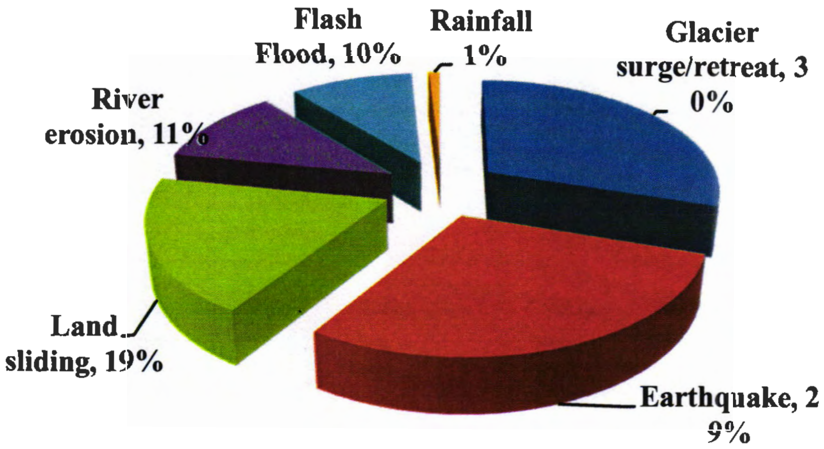


Fig. 3.56: Percentage share of different hazards in study area

CONCLUSION

The glacial environment of the three Himalayan ranges of Pakistan was investigated through integrated RS and GIS techniques. The findings of the study revealed altogether 50 new glacial lakes with area greater than 2000 sq.km over the period of 2001- 2013.It was concluded that in these glaciated mountains of Northern Pakistan the so-called mountainous hazards (among other debris flows, earth quake, flash floods, rockfall, or snow avalanches) are omnipresent. The most important events with highest potential for glacial lakes formation are glacier recession followed by earthquake induced landslide and river erosion. Several large landslide events in NorthernPakistan and surrounding areas are mostly naturally activated like Earth-quake in combination with destructive rock avalanches. The severity of these hazards is related to the geographic location. It was also concluded that glacial lakes formation and expansion are closely related with climate change which indicate the prevalence of global change influence on this mountainous range. On the basis of our findings it is suggested that educating yourself on how to best manage the glacier variation and to get awareness is important to avoiding or prolonging the adverse effects on local population due to GLOF. However, the lack of accurate and adequate researches and confirmed evidence create many problems and confusions about how much retreat and surge of glaciers is occurring across the Himalayan ranges and what would be the change under various conditions. As such data and studies are inadequate to solve this problem related to general assessment of all other factors for glacial lakes formation at various elevations in the HKH Region, a regular monitoring of glaciers and associated lakes is essential in context of possible increase in global warming to mitigate high risk of future flood hazards in this fragile mountain ecosystem of Northern Pakistan. On the other hand study of glacial lakes is utmost important to reserve the resources as the stable lakes is most important source of water for agriculture, industrial and hydropower development in nearby villages. Secondly lakes in these valleys (e.g. gilgit, hunza, shoyok, shigar) are of great attraction in context of tourism, prosperity and economic development of country.

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