

IMPACTS OF CLIMATE CHANGE: GLACIAL LAKE OUTBURST FLOODS (GLOFS)

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ABSTRACT

Worldwide receding of mountain glaciers is one of the most reliable evidences of the changing global climate. In high mountainous terrains, with the melting of glaciers, the risk of glacial related hazards increases. One of these risks is Glacial Lake Outburst Floods (GLOFs). As glaciers retreat, glacial lakes form behind moraine or ice ‘dams’. These ‘dams’ are comparatively weak and can breach suddenly, leading to a discharge of huge volume of water and debris. Such outbursts have the potential of releasing millions of cubic meters of water in a few hours causing catastrophic flooding downstream with serious damage to life and property. Glacier thinning and retreat in the Sikkim Himalayas has resulted in the formation of new glacial lakes and the enlargement of existing ones due to the accumulation of melt-water. Very few studies have been conducted in Sikkim regarding the impacts of climate change on GLOFs. Hence a time-series study was carried out using satellite imageries, published maps and reports to understand the impacts of climate change on GLOFs. The current study is focussed on finding the potential glacial lakes in Sikkim that may be vulnerable to GLOF. The results show that some of the glacial lakes have grown in size and are vulnerable to GLOF. Though extensive research is required to predict GLOFs, it is recommend that an early warning system, comprising of deployment of real time sensors network at vulnerable lakes, coupled with GLOF simulation models, be installed for the State.

KEYWORDS: *Climate Change, Glacier, Glacier Retreat, Glacial Lake Outburst Floods (GLOFs), Remote Sensing, Moraine Dammed Lakes, Snout*



Remnants of Glacial Lake Outburst Flood (GLOF) in Teen-kune Pokhri, below Mt. Pandim in West Sikkim
Photo courtesy: Sandeep Tambe



Fig. 1: Chho Lhamo (5217 m) in North Sikkim, one of the lakes having GLOF potential

Glacial lakes in the Himalaya are known to have mostly formed within the last 5 decades. Warming in the Himalayas in the last three decades has been between 0.15°C and 0.60°C per decade (Shrestha et al. 2010). As a result of global warming, the glacial lakes are increasing in number and size. The GLOF events have trans-boundary effect resulting in loss of lives, as well as the destruction of houses, bridges, fields, forests, hydro-power stations, roads, etc. Regular monitoring of glaciers and glacial lakes and adaptation measures including early warning systems and mitigation measure are required in areas vulnerable to GLOF (Bajracharya 2006).

Effects of climate change like unseasonal rainfall, lake outbursts, rising temperatures, increased flooding, flash floods, rock avalanches from destabilized slopes leading to road blockages are already being experienced in Sikkim. Very few studies have been conducted in Sikkim regarding the impacts of climate change on GLOFs so far. It is imperative that the State builds a knowledge database on the climate change so that it can prepare itself for reducing the impacts and adapting to the forecasted changes. Our knowledge of GLOFs is very limited and advanced research needs to be undertaken to predict and reduce their effects.

Remote sensing with its advantages of spatial, spectral and temporal availability of data covering large and inaccessible areas within short time has become a very handy tool in assessing and monitoring disaster prone zones in high altitude regions. Moraine dam lakes have been mapped and monitored by using remote sensing data in the Sikkim Himalayas. The glacial lakes were mapped and monitored from the disaster point of view and in relation to climatic variations.

The frequency of GLOF events is increasing in the Hindu Kush Himalayan (HKH) region since the second half of the 20th century due to the combined effects of climate change and deforestation. Satellite observation of the mountain top lakes in the region have revealed a steady increase in the size and volume of many of these glacial lakes at high altitudes, enhancing the possibility of a devastating outburst flood affecting sizeable populations, damaging precious socio-economic infrastructure and development assets in the Himalayan belt (UNDP 2010).

CLIMATE CHANGE

“Climate Change” in Intergovernmental Panel on Climate Change (IPCC 2007) parlance refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity. As per United Nations Framework Convention on Climate Change (UNFCCC 1992) usage, it refers to change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods.

Globally, the impacts of climate change include among others, rising temperatures, shifts in rainfall pattern, melting of glaciers and sea ice, risk of glacial lake outburst floods (GLOFs), sea level rise and an increased intensity and frequency of extreme weather events (Ganguly et al. 2010). Global warming is the prime factor for the accelerated glacial melt and retreat, giving birth to hazardous glacial lakes in the Sikkim Himalayas.

GLACIAL LAKE OUTBURST FLOODS (GLOFS)

The acronym GLOF is used for glacier floods caused by the drainage of naturally dammed lakes in the glacier, on or at the margin of glaciers. GLOFs are not a new phenomenon but with the worldwide receding of glaciers and rising temperature the probability of their occurrences has risen in many mountain ranges. “Glacier floods represent in general the highest and most far reaching glacial risk with the highest potential of disaster and damages” (Richard et al. 2003).

A lake outburst can be triggered by several factors: ice or rock avalanches, the collapse of the moraine dams due to the melting of ice buried within, the washing out of fine material by springs flowing through the dam (piping), earthquakes or sudden inputs of water into the lake e.g. through heavy rains or drainage from lakes further up-glacier. Self-destruction is caused by the failure of the dam slope and seepage from the natural drainage network of the dam (WWF Nepal Program 2005).

IMPACT OF CLIMATE CHANGE ON GLACIERS AND GLACIAL LAKES

The climatic change/variability in recent decades has made considerable impacts on the glacier lifecycle in the Himalayan region. The Himalayas are geologically young and fragile and are vulnerable to even insignificant changes in the climatic system (Lama et al. 2009). Studies confirm that many glaciers of the Sikkim Himalayas are leaving glacial lakes with increasing intensity, which in fact is corroborating with the intermediate effects of long term Climate Change by majority of scientists.

Glacier thinning and retreat in the Sikkim Himalayas has resulted in the formation of new glacial lakes and the enlargement of existing ones due to the accumulation of melt-water behind loosely consolidated end-moraine dams. Such lakes are inherently unstable and subject to catastrophic drainage, they are potential sources of danger to people and property in the valleys below them (ICIMOD 2011). Local communities living in the region are dependent upon the lakes for their livelihood regardless of whether they are settled or nomadic (SAC 2011).

Recent studies being carried out by Centre for Development of Advanced Computing (C-DAC), Pune jointly with Sikkim State Council of Science & Technology, Gangtok, have shown that many glacial lakes in Sikkim Himalayan region have grown over the years revealing the impact of climate change on glacial lakes and associated hazards.

The state of Sikkim shelters many Glaciers, mainly Zemu Glacier, Rathong Glacier and Lhonak Glacier. The status of these Glaciers has become a measuring stick of climate change (SAC 2010). The East Rathong Glacier is one of the important glaciers of Sikkim which has been affected by climate change. The glacier has retreated significantly since 1965 and a marked shift in its Snout position has been observed. A glacier terminus, or snout, is the end of a glacier at any given point in time, the position of which is impacted by localized or regional temperature change over time (NSIDC 2007). A glacial lake is in formation behind the terminal moraines due to blockage of the melt water. Its current state as observed today is shown in Fig. 2 below.

DATABASE AND METHODOLOGY

Various types of data such as satellite borne remote sensing data and other published maps and reports constitute the database necessary for the mapping and monitoring of glacial lakes in the Sikkim Himalayas. Multi-date Indian Remote Sensing Satellites - IRS-1A/1B/1C/1D/P6, United States Geological Survey (USGS) Declassified Imagery (CORONA, KH-Series), Land Observation Satellites (LANDSAT- MSS, TM, ETM), and Google Earth, etc. data in digital format were used in conjunction with secondary or collateral data.



Fig. 2: East Rathong Glacier, West Sikkim – glacial geomorphological features such as glacial lake, snout, moraines and the parent glacier are seen. Photo courtesy: Binay Kumar, May 2011)

All the glacial lakes of Sikkim were demarcated and delineated using remote sensing data, published maps & reports, and field data. Moraine dammed lakes are an important component of glacier studies. These lakes are important in monitoring of disaster prone zones in high altitude regions. Time-series analysis of the glacial lakes was carried out with the available cloud-free satellite imageries for the region. Geographic Information System (GIS) software package was used for creation of digital database and data analysis.

CRITERIA FOR IDENTIFICATION, SELECTION AND MONITORING OF GLACIAL LAKES

1. Lake area expansion over the years
2. Increase in water level of glacial lakes due to expansion of lake area
3. Formation of new glacial lakes
4. Significant glacier retreat
5. Lakes located at an altitude 4,500 m and above
6. Area of lakes more than 0.05 sq. km.
7. Position of the lakes – near to ablation area of the glacier
8. Proximity of the glacial lakes to the parent glacier
9. Lakes formed due to the damming of the channel flow by the end/terminal moraines

Glacial Lakes Monitored for the study (1965 to 2010)

In Teesta and Rangit basins of Sikkim Himalayas moraine-dammed lakes were observed from 1965 to 2010 using satellite imageries. For the current study, lakes meeting most of the above criteria were identified and monitored. The glacial/moraine dammed lakes which were further monitored and mapped are listed below:

NORTH SIKKIM

- a. Gurudongmar Chho Complex* (3 lakes denoted as A, B and C)
 - i. Gurudongmar Chho “A” (elevation 5,174 m)
 - ii. Gurudongmar Chho “B” (elevation 5,253 m)
 - iii. Gurudongmar Chho “C” (elevation 5,218 m)
- b. Chho Lhamo (elevation 5,217 m)
- c. Khangchung Chho (elevation 5,325 m)
- d. Lachen Khangse Chho (elevation 5,181 m)
- e. Glacial Lake feeding river Shako Chhu (elevation 4,975 m)
- f. Khora Khang Chho (elevation 5,097 m)
- g. South Lhonak Chho (elevation 5,210 m)
- h. Lhonak Chho (elevation 5,451 m)

WEST SIKKIM

- a. Bhale Pokhari (elevation 4,727 m)
- b. Glacial Lake feeding river Tikip Chhu (elevation 4,877 m)

***Gurudongmar Chho Complex:** The Gurudongmar Chho Complex in the current study comprises of 3 lakes - Gurudongmar Chho (elevation 5174 m, denoted as “A”) and two other lakes located at the terminus of Gurudongmar glacier (elevations 5253 and 5218 m and denoted as “B” and “C” respectively) feeding the Gurudongmar lake.

ANALYSIS

Glaciers continually adjust their size and flow speed to seek equilibrium with climate. By comparing newer remote-sensing derived glacial lake outlines with older data sets derived from topographic maps or older imagery, the changing face of glacial lakes could be seen.

Monitoring and tracking of the lakes in West and North Sikkim has revealed that quite a few of them are expanding due to accelerated glacial retreat and melting due to climate change impacts. The lakes have been increasing in size and volume since 1965. Their area has increased significantly in about 45 years and this indicates the lakes are important from the disaster point of view and also in view of climatic variations in last three decades. In addition, new lakes have also developed due to glacier retreat and melting. During the retreat the glaciers leave behind moraines (accumulation of boulders, stones or other debris) in the valley. A Moraine-laden valley in North Sikkim, carved by a retreated glacier is shown in Fig. 3.

Field observations give an impression of a past GLOF event in the Sebu Chhu valley, North Sikkim. The wide spread of the moraines in the valley might have been carried downstream by the flood waters from the Sebu

Chho, which appears to have breached in the past (Fig. 14). Local information also supports an event of a flash flood in the Sebu Chhu Valley. The change in the area of the glacial/moraine dammed lakes monitored since 1965 has been shown in Table-1.

Table-1: Statistics showing growth in the area of glacial/moraine dammed lakes over the years. The lake areas are in sq. km.

Lake Name/Year	1965	1976	1989	1997	2000	2005	2010
Gurudongmar Chho A	1.048	1.099	1.099	1.099	1.104	1.115	1.134
Gurudongmar Chho B	0.249	0.322	0.925	1.046	1.046	1.073	1.076
Gurudongmar Chho C	0.480	0.687	0.718	0.728	0.732	0.745	0.745
Chho Lhamo	0.649	0.963	1.031	1.031	1.031	1.031	1.031
Khangchung Chho	1.178	1.261	1.605	1.630	1.661	1.661	1.734
Lachen Khangse Chho	0.360	0.370	0.516	0.523	0.586	0.613	0.613
Glacial Lake feeding river Shako Chhu	0.273	0.409	0.561	0.561	0.561	0.561	0.561
Khora Khang Chho	0.166	0.217	0.269	0.296	0.302	0.342	0.351
South Lhonak Chho	0.242	0.251	0.410	0.633	0.691	0.794	1.028
Lhonak Chho	0.231	0.282	0.418	0.460	0.494	0.652	0.656
Bhale Pokhari	0.090	0.104	0.108	0.114	0.114	0.114	0.114
Glacial Lake feeding river Tikip Chhu	0.069	0.108	0.214	0.257	0.308	0.311	0.311



Fig. 3: Moraine-laden glacier valley. Moraines are left behind by the retreating glaciers. Also seen is the flow of melt water feeding Sebu Chhu, North Sikkim.

Photo courtesy: Binay Kumar, Nov 2010



Fig. 4: Zemu river originates from Zemu glacier and lateral landslides pose the danger of damming the river and causing floods downstream

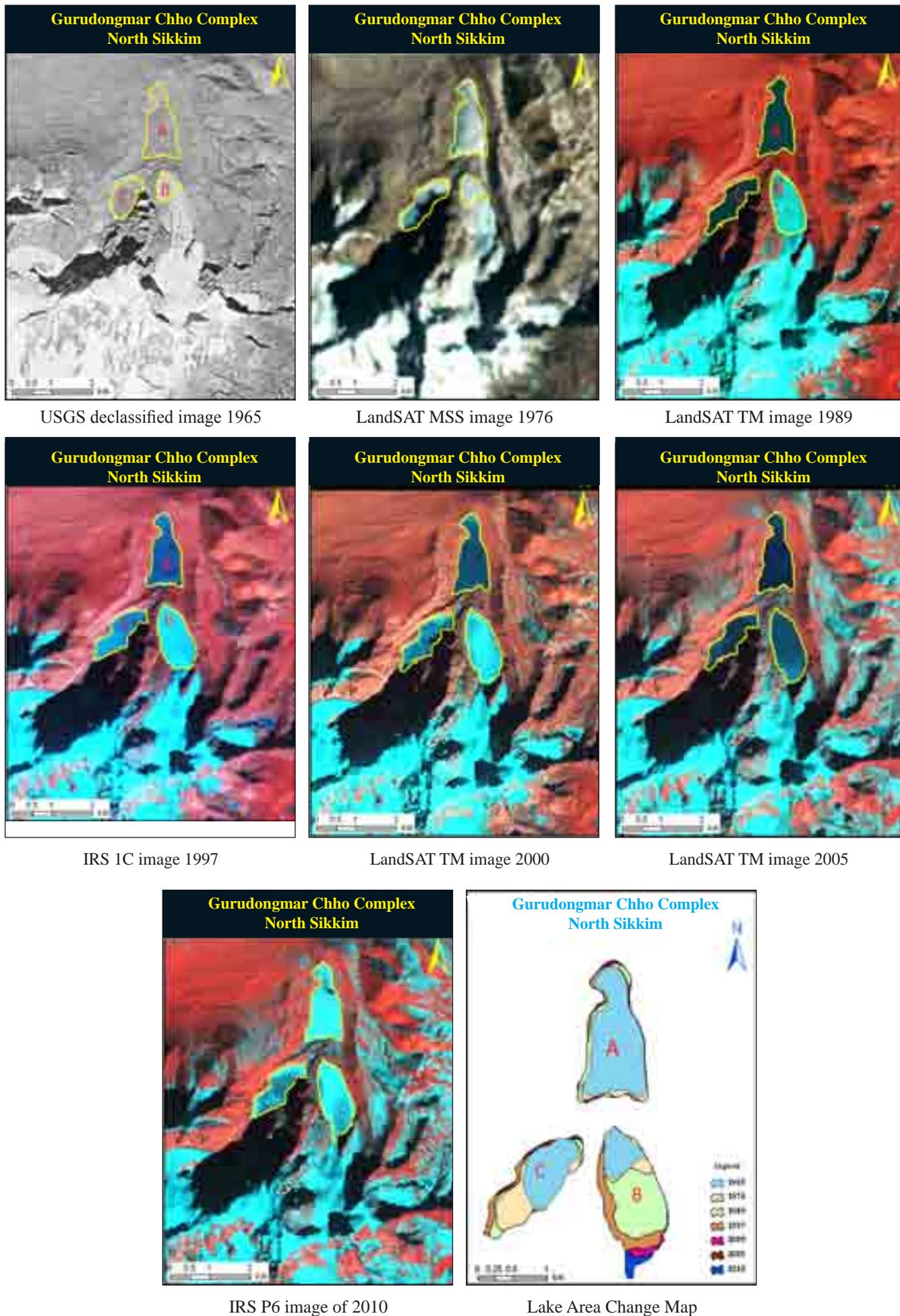


Fig. 5: Monitoring of Gurudongmar Chho complex, North Sikkim

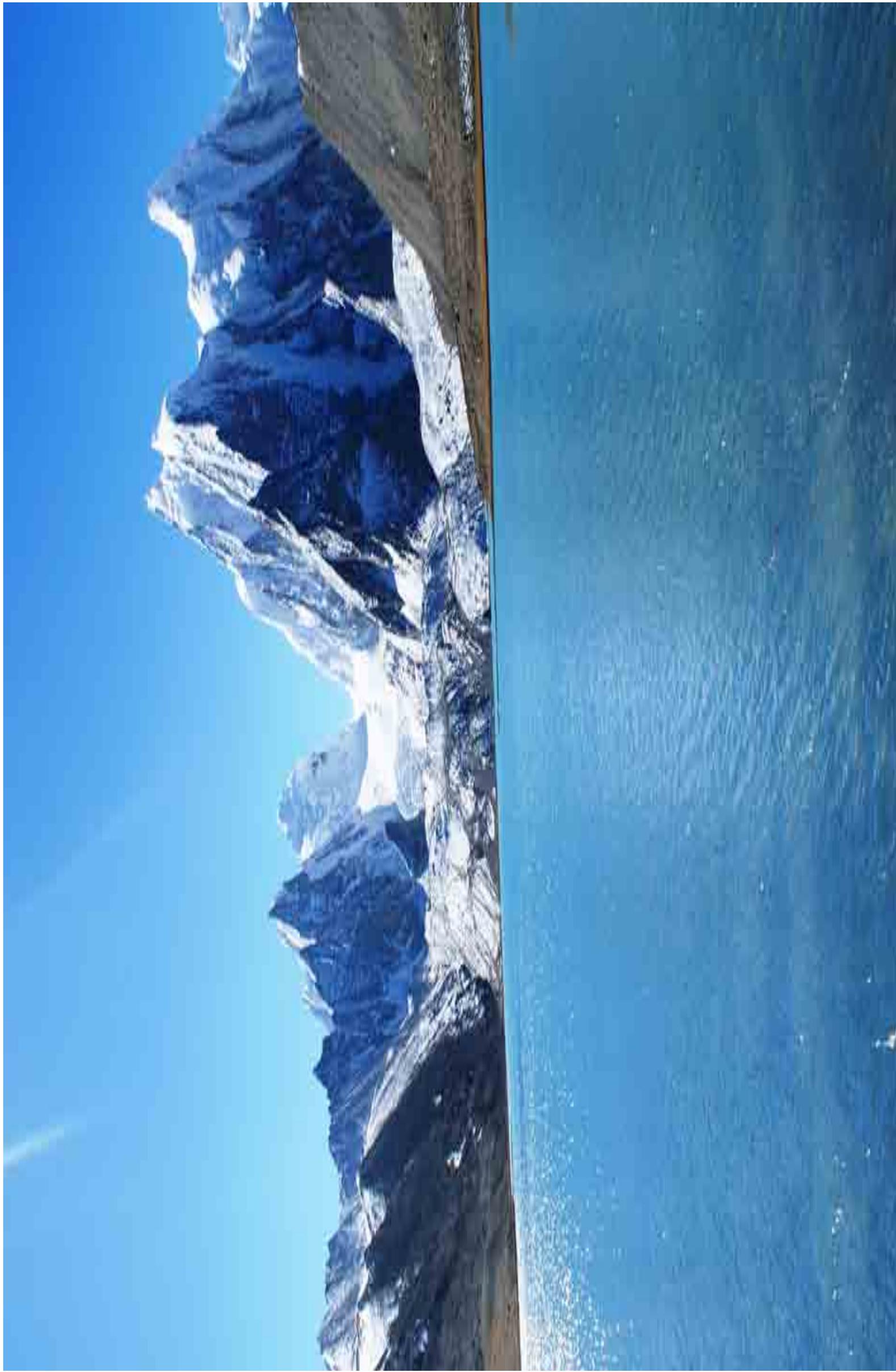


Fig. 6: Panoramic view of the frozen moraine dammed lake feeding Tikip Chhu, West Sikkim. Photo courtesy: Mr. Safal Pradhan, May 2011

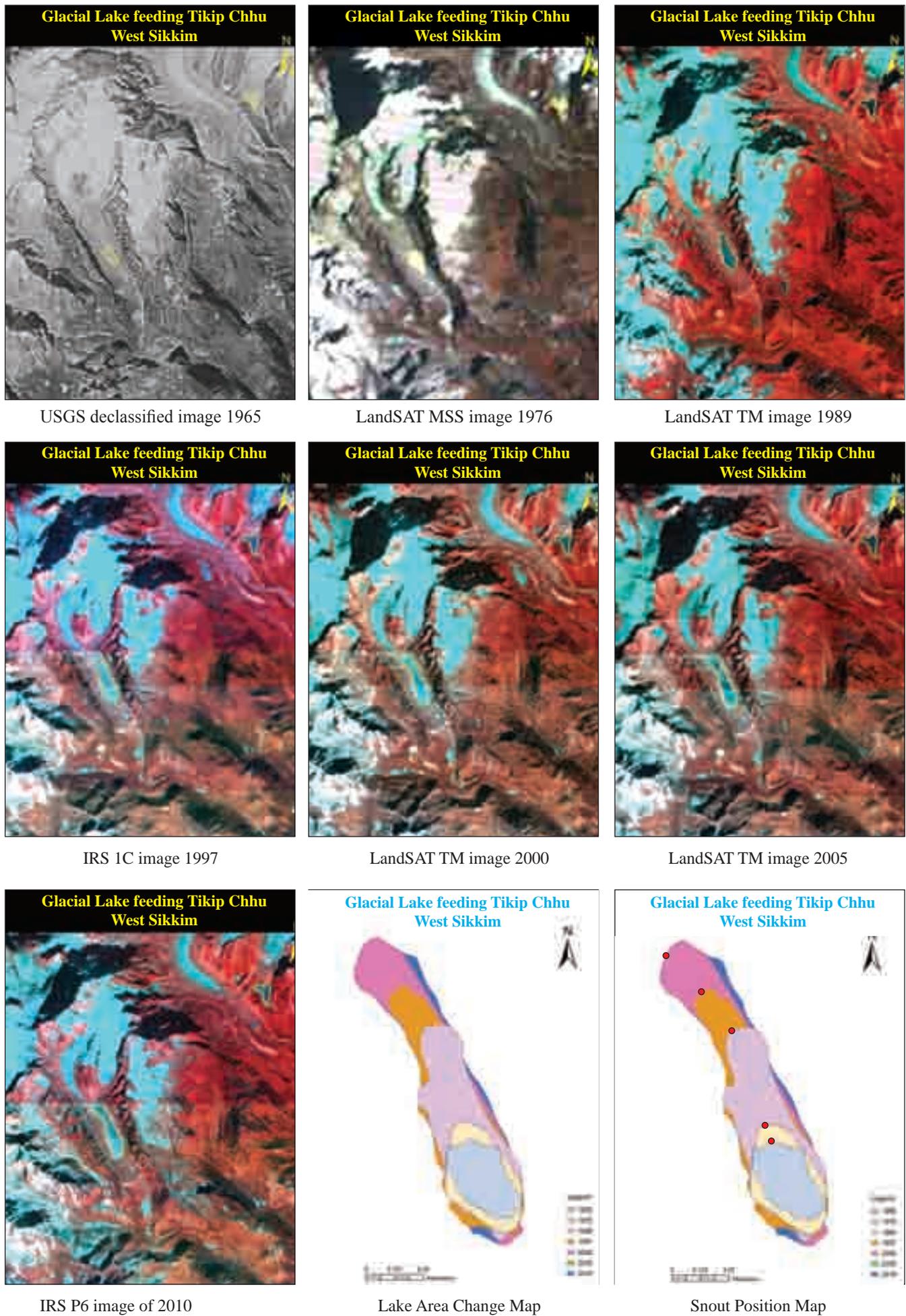


Fig. 7: Monitoring of Glacial Lake feeding Tikip Chhu, West Sikkim



Fig. 8: Panoramic view of the frozen moraine dammed lake feeding Tikip Chhu, West Sikkim. Photo courtesy: Mr. Safal Pradhan, May 2011

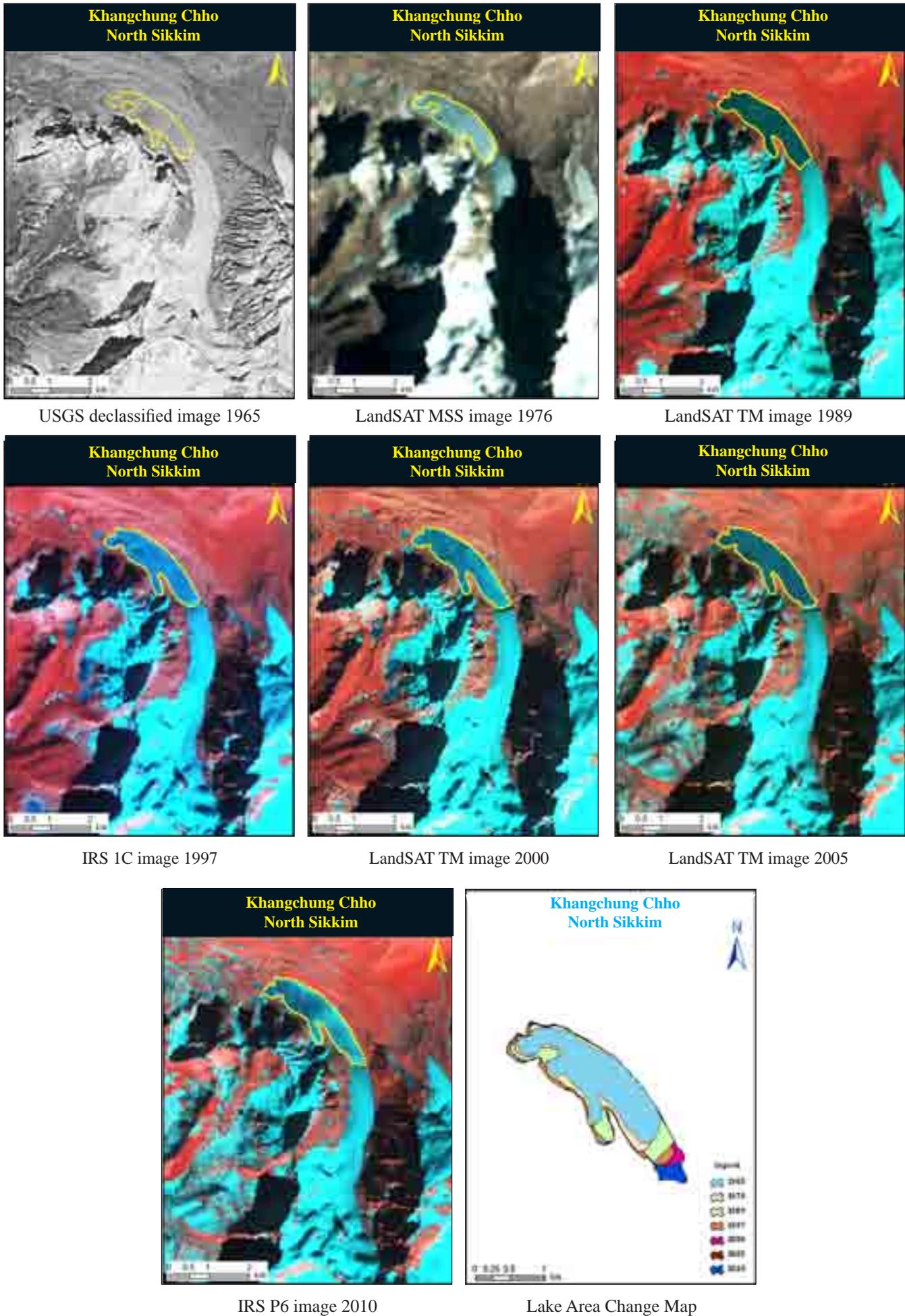


Fig. 9: Monitoring of Khangchung Chho, North Sikkim



In 2007, a flash flood washed away the riverine vegetation along the Zemu river

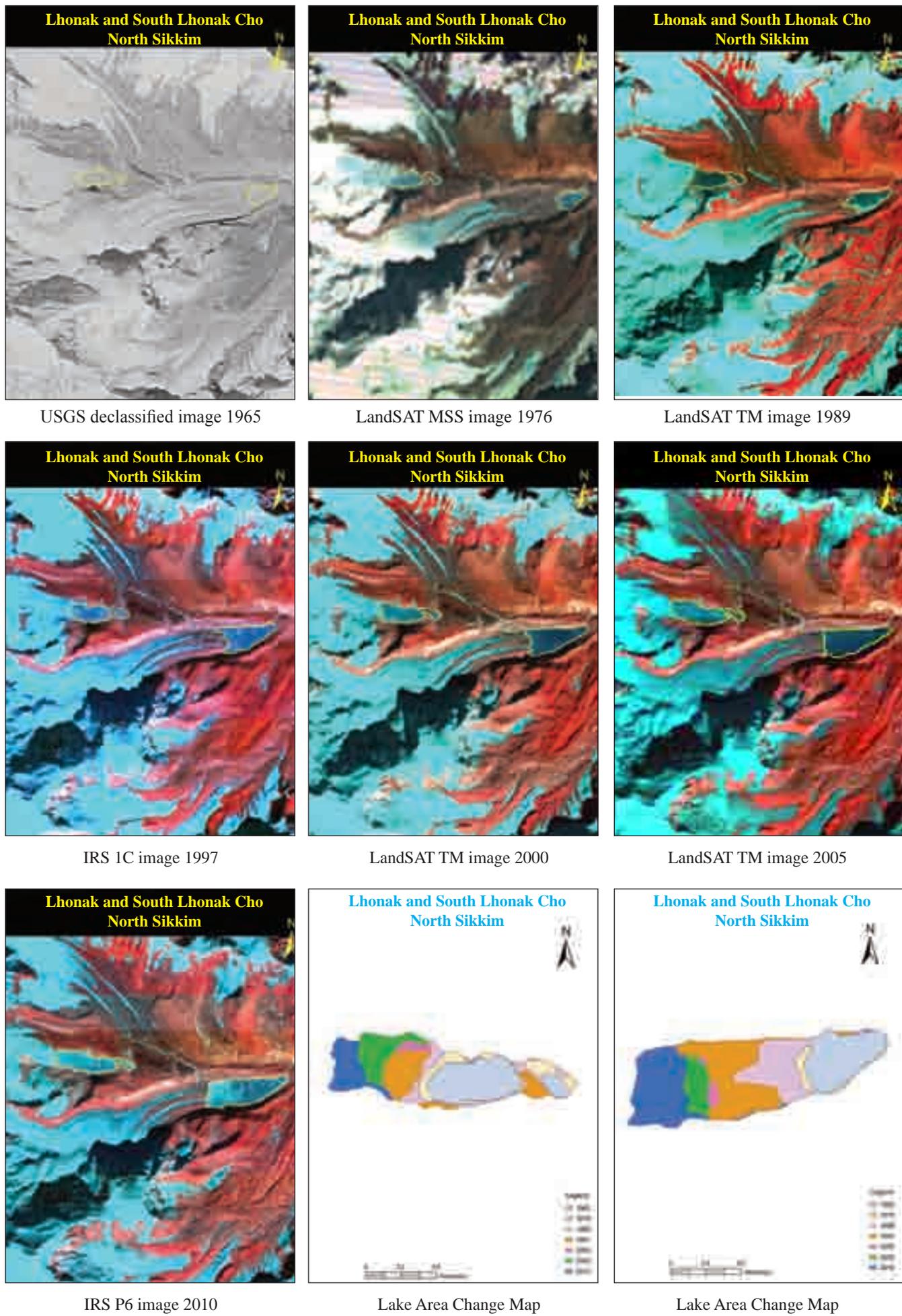


Fig. 10: Monitoring of Lhonak and South Lhonak Chho, North Sikkim

RESULTS / FINDINGS

The climatic change/variability in recent decades has made considerable impacts on the glacier lifecycle in the Sikkim Himalayas. The melting of glaciers and accumulation of melt water in the lakes has significantly increased the volume of water in the glacial lakes. The areal expansion of the glacial lakes monitored under the current study has been graphically represented in the Fig. 11 below.

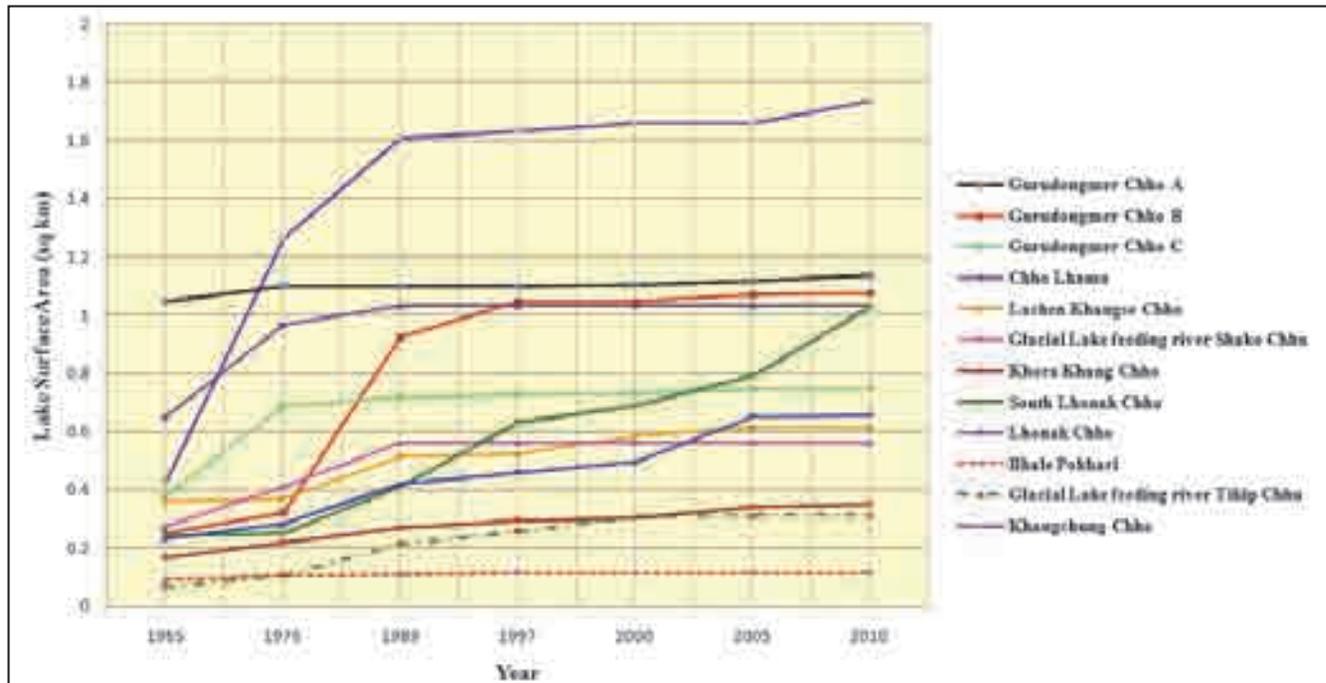


Fig. 11: Areal expansion of glacial lakes between 1965 and 2010.

From the graph it is evident that other than lakes Gurudongmar Chho “A” and Bhale Pokhari, the area of all other lakes has increased significantly between 1965 and 1989. Between 1989 and 2010, other than the lakes Chho Lhamo, Gurudongmar Chho “A”, “C”, the glacial lake feeding river Shako Chhu, and Bhale Pokhari, the area of other lakes has changed. Field observations carried so far confirm this. This significant trend in the increase in area of most of the glacial lakes may be attributed to the global warming phenomenon. The rising trend in the graphs signifies the impact of climate change on glaciers. The increase in area of glacial lakes behind unstable moraine dams poses more danger of GLOFs. The stagnation in areal growth of the lakes between 1989 and 2010 may be attributed to equilibrium between the melt water in-flow to the lake and the water getting drained out of the lake.

The graphical representation of the areal change of glacial lakes between 1965 and 2010 has been shown in Fig. 12 and Fig. 13.

Glacial Lake Area Change

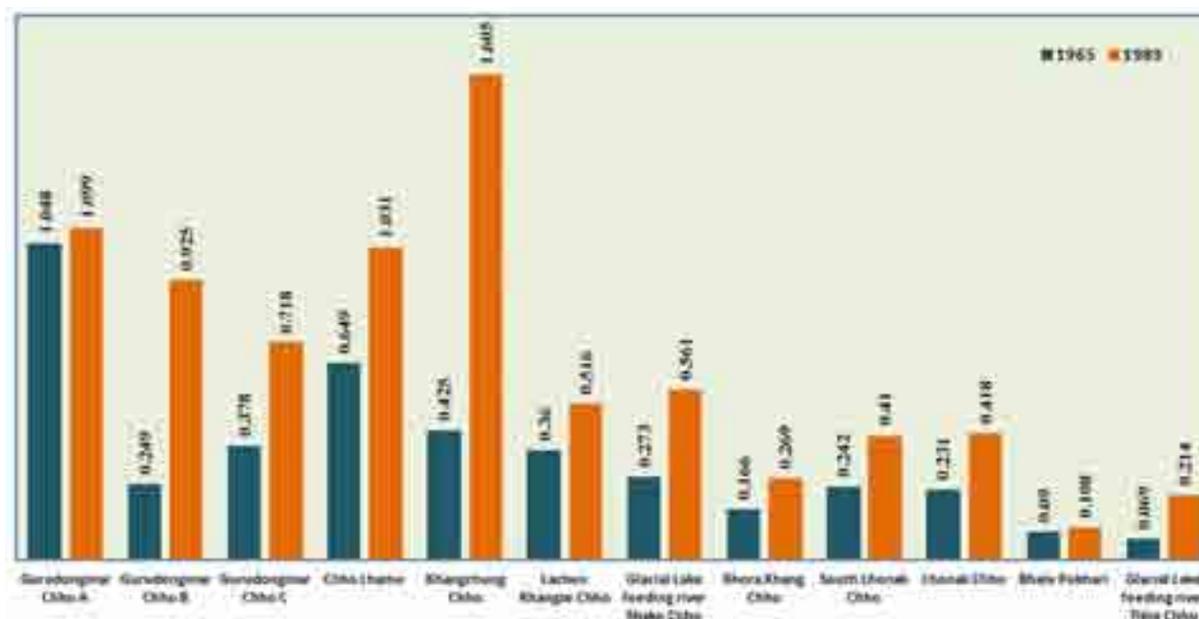


Fig. 12: Change in lake area between 1965 and 1989.

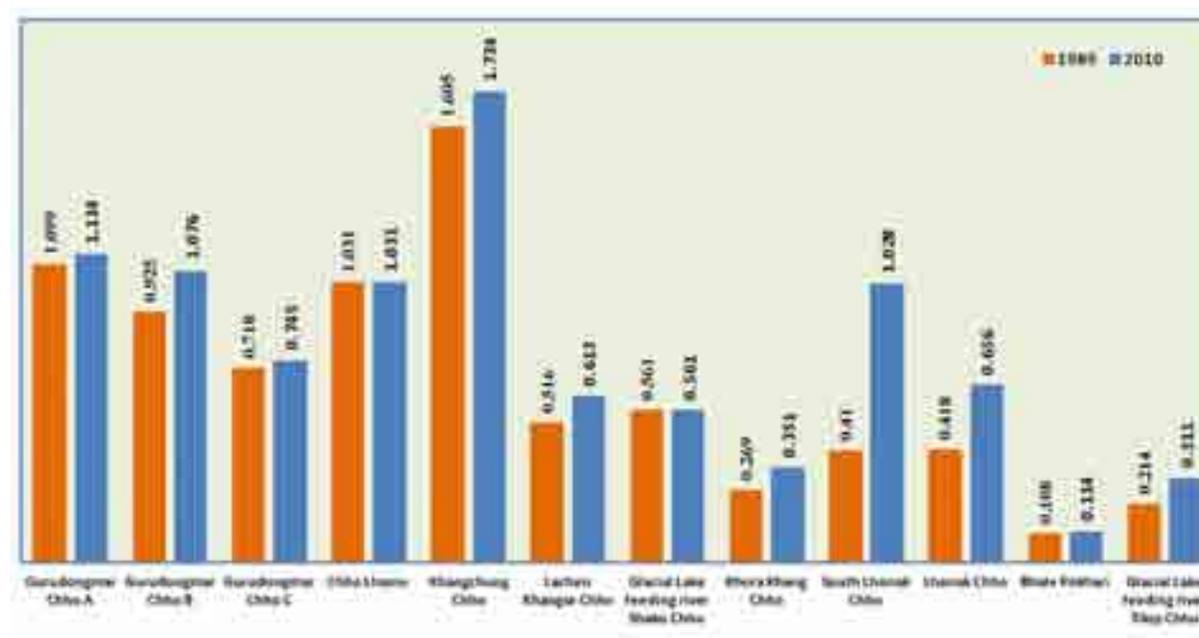


Fig. 13: Change in lake area between 1989 and 2010.

The area of lake “B” in the *Gurudongmar Chho Complex* has increased nearly 4 times between 1965 and 1989, whereas of lake ‘C’, it’s nearly double. The significant increase in the areas of lakes “B” and “C” is a clear indicator of the glacier retreat/melt and accumulation of more melt water in the moraine dammed lakes, as shown in Fig 12 and Fig. 13. Between 1989 and 2010, Gurudongmar Chho “B” has grown by one-sixth of its size in 1989. The volume of water these 3 lakes together hold could be easily estimated. The risk associated with the GLOF event, in case any of the above dams particularly “B” and “C” break could easily be perceived.

The *Khanchung Chho*, origin of the River Teesta is another moraine dammed lake which has grown noticeably over past few years, as evident in Figs. 9, 11 12 and 13. Its area has increased nearly 1.5 times between 1965 and 1989 and approximately one-tenth of its size in 1989 between 1989 and 2010. The parent glacier is in contact with the lake which further enhances the vulnerability of the lake to cause GLOF.



Fig. 14: Green Lake (Tikuchia Pokhari), West Sikkim - a moraine dammed lake formed due to the retreat of glacier near Goecha La. Photo courtesy: Swapnil Awaghade, May 2011

The *Chho Lhamo* (Fig. 1), a glacial lake that has grown in size significantly is located near the border of Sikkim and Tibet Autonomous Region (TAR) and feeds River Teesta. In 1989, its area has increased by 1.5 times its size in 1965. Since then its area has remained almost same till 2010.

The increase in area of the *Lhonak and South Lhonak* glacial lakes over the last 45 years is significant. Both these lakes have grown in area by 2 times between 1965 and 1989. Lhonak has grown nearly 1.5 times and South Lhonak nearly 2.5 times of their initial size in 1989, as shown in Fig. 10, Fig. 12 and Fig. 13. The increase in size is not the only factor that lists this lake as a potential GLOF source. An earthquake of magnitude 4.9 of Sept 21, 1991 (as reported by United States Geological Survey) near the parent glacier feeding the South Lhonak Lake and the recent earthquake (magnitude 6.9) of Sept 18, 2011 approximately 70 km from the lakes and future earthquakes may trigger the GLOF events. In future also the earthquakes may occur considering the fact that the state of Sikkim falls in Zone-IV of the Indian Seismicity Chart.

The *moraine dammed lake feeding Tikip Chhu* (Fig. 8) in West Sikkim has increased noticeably by nearly five times since 1965. The areal growth of the lake and the position of snout (terminus of glacier) over the years have been depicted in Fig. 7. It is very interesting to note that this lake is newly formed due to glacier retreat and is not present in Survey of India Topographic sheets.

The *moraine dammed lake feeding Shako Chhu* has increased by nearly two times between 1965 and 1989 and the area remains almost same thereafter till 2010.



Fig. 15: Glacial Lake at the end of Changme Khangpu Glacier, North Sikkim. Also seen the moraines spread around the area, giving an impression of a past GLOF event at Sebu Chho.
(Photo courtesy: N. P. Sharma, Nov 2010)

Another lake in West Sikkim is **Green Lake (Tikuchia Pokhari)**, which is a moraine dammed lake, has formed due to the retreat of glacier near Goecha La is shown in Fig. 14. Field observation show that the lake is surrounded by boulders (moraines) and there is considerable seepage of water from the southern part of lake.

GLOF EARLY WARNING SYSTEM IN SIKKIM – A C-DAC INITIATIVE

Although extensive research is required to predict GLOFs, an early warning system capable of providing alerts in case there is a threat of GLOF is essential. C-DAC has taken up a project funded by the Department of Information Technology, Government of India to set up a GLOF Early Warning System at Sikkim by deploying field sensors at 2 lakes on pilot basis. C-DAC has taken up the challenge to design and develop real time field sensors for recording rise in water level in selected moraine dammed lakes. The field sensor data will be transmitted through satellite communication network and will be used in the flood simulation model for prediction of GLOF/flash floods, areas likely to be inundated/affected by GLOFs, and Impact assessment of GLOFs.

CONCLUSION

From the time-series study carried out using satellite imageries of the Sikkim Himalayas, to understand the climate change induced risks and vulnerabilities of GLOFs, it is evident that many glacial lakes have expanded over the years. As a result, many big glaciers have melted rapidly, forming a large number of glacial lakes.



Fig. 16: : South Lhonak Chho depicting the moraine dam breach-section (shown in red box on inset picture), an evidence of past GLOF event. There is a possibility that the lake may refill & may cause GLOF.

Due to an increase in the rate at which ice and snow melted, the accumulation of water in these lakes started increasing rapidly. Sudden discharge of large volumes of water with debris from these lakes potentially causes glacial lake outburst floods (GLOFs) in valleys downstream. These result in serious death tolls and destruction of valuable natural resources, such as forests, farms, and costly mountain infrastructures. The Hindu Kush-Himalayan region has suffered several GLOF events originating from numerous glacial lakes, some of which have trans-boundary impacts (*Bajracharya et. al., 2006*).

The areal growth of the lakes Gurudongmar “A”, Chho Lhamo and Bhale Pokhari (Fig. 11) seems to have ceased since the last 2 decades and may not be an immediate threat, but nevertheless their vulnerability remains high from the GLOF point of view. All other lakes whose areas have increased significantly over the last 45 years should be considered dangerous and GLOF prone.

It is vital to identify potentially dangerous glacial lakes and the risks they pose, and highlight the critical ones. Some glacial lakes may have caused GLOF in the past and may breach again in future. Hence, identification and monitoring of such lakes need to be carried out, by evidences of past GLOF events. Remote sensing imageries are very useful in monitoring of the glaciers and glacial lakes as new glacial lakes are being created and existing ones continue to grow. Regular monitoring of glacial lakes, identification of critical lakes and GLOF prone areas, installation/deployment of field sensors in glacial lakes, setting up of early warning system, creating awareness among the people and adopting mitigation measures, may reduce the intensity of the disaster associated with GLOFs.

Though extensive research is required to predict GLOFs, it is recommend that an early warning system be installed for the State. The early warning system should be capable of providing alerts to the Government authorities in case there is a threat of GLOF. Deployment of real time sensors network at vulnerable lakes, capable of measuring rise and discharge of water, will enable the authorities to set up an early warning system. The early warning system coupled with GLOF simulation models capable of predicting the time of arrival of

the flash flood and showing the flooded areas downstream will enable the local authorities to take precautionary measures in the event of a GLOF.

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ACRONYMS

C-DAC – Centre for Development of Advanced Computing

ETM – Enhanced Thematic Mapper

GIS – Geographic Information System

GLOF – Glacial Lake Outburst Flood

ICIMOD - International Centre for Integrated Mountain Development

IPCC - Intergovernmental Panel on Climate Change

IRS – Indian Remote Sensing Satellite

LandSAT – Land observation Satellite

MSS – Multi Spectral Scanner

NSIDC- National Snow and Ice Data Center

SAC – Space Applications Centre (ISRO)

TM – Thematic Mapper

UNDP - United Nations Development Program

UNFCCC - United Nations Framework Convention on Climate Change

USGS – United States Geological Survey

WWF – World Wildlife Fund

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