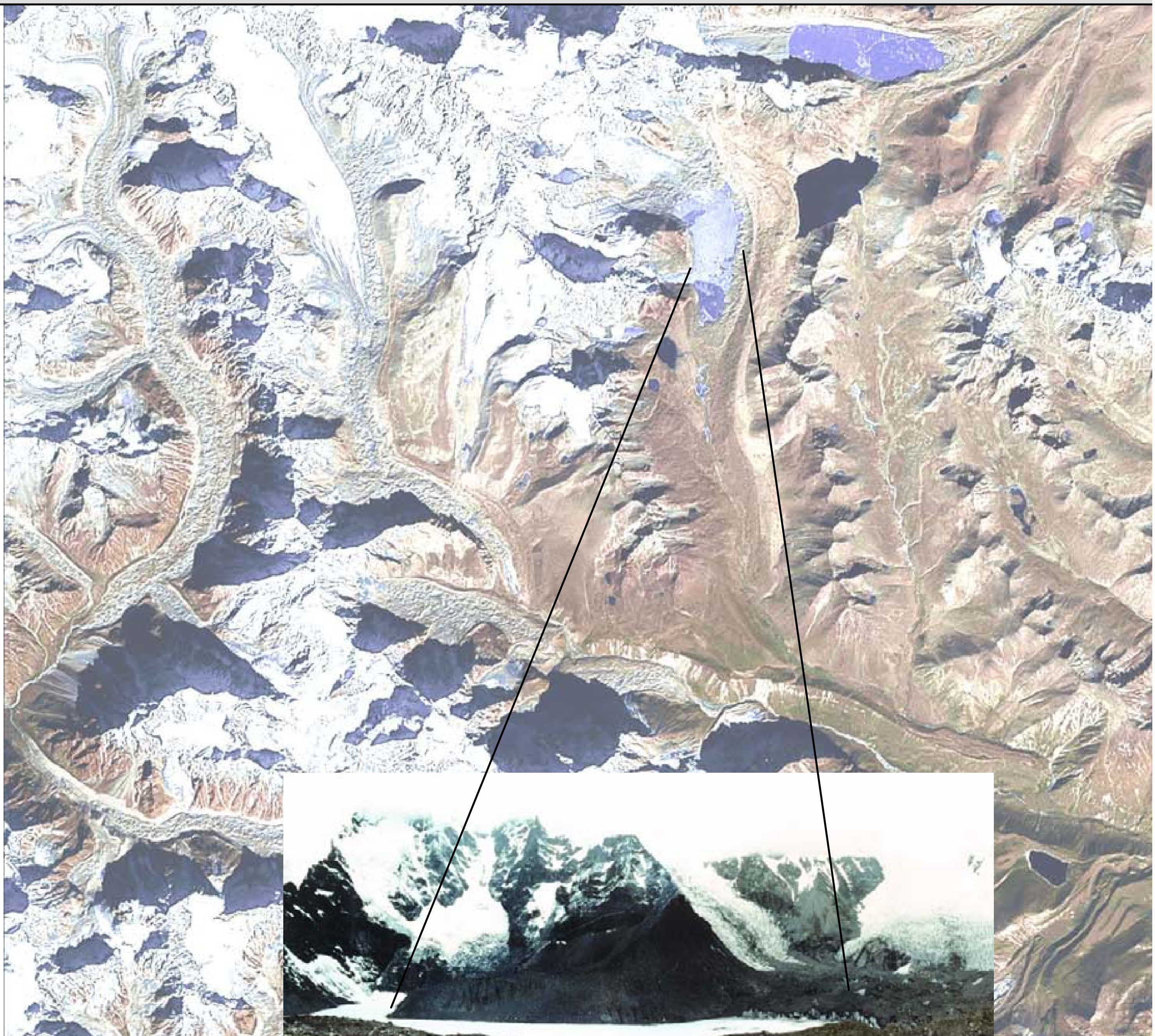
Monitoring of Glaciers and Glacial Lakes from 1970s to 2000 in Poiqu Basin, Tibet Autonomous Region, PR China



Monitoring of Glaciers and Glacial Lakes from 1970s to 2000 in Poiqu Basin, Tibet Autonomous Region, PR China

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ABSTRACT

The study using different satellite data and topographic maps since 1977 and available reports shows remarkable retreat of glaciers due to climate change in the Poiqu basin in Xixiabangma area – a common basin between China and Nepal. Poiqu River in the downstream in Nepal is named SunKoshi-BhoteKoshi.

At present, there are about 150 glaciers covering 11 percent of area within Poiqu basin in China. The study reveals that about five percent of the glaciers from the entire basin have vanished since the last three decade. As a result of glaciers retreat, glacial lakes are growing in alarming rate.

Some of the glaciers , such as the valley glaciers with IDs 5O191B0029 (mother glacier of LumuChimi glacial lake) and 5O191C0009 (mother glacier of GangxiCo glacial lake) on the eastern slope of the Xixiabangma decreased by about 0.055 km^2 and 0.059 km^2 in area and retreated around 45 m and 68 m in length respectively per year since 1977. Similarly the analysis on the five valley glaciers on the northern slope of the Laptshegang Mountain had also shown the glacier shrunk by average of 0.028 km^2 in area and retreated about 20m per year.

Some of the lakes, such as LumuChimi and GangxiCo lakes have grown almost double in size. Nine glacial lakes pose potential threat of glacial lake outburst floods (GLOF) which most often have devastating effects on local people and the surrounding environment.

Such GLOF events may damage existing infrastructure such as hydropower and roads, and agriculture land in the downstream to the lower riparian country. There is need for regional cooperation for exchange of scientific information and to carry out detailed field investigation in the area to evaluate the possible damage in downstream area. Early Warning Systems (EWS) at the potential dangerous lakes and downstream areas are necessary to minimize and mitigate the effects of such natural disasters.

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1 GENERAL

1.1 Introduction

Poiqu basin is situated in the southwest ofTibet Autonomous Region of P R China between the latitudes 26°37' to 28°32'N and longitudes 85°43' to 86°18'E. It is a trans-boundary basin, the Poiqu River in China and Sun Koshi - Bhote Koshi in Nepal (Figure 1.1). The total basin area is 3,393.7 km^2, where 2,006.5 km^2 is within China and 1,387.2km^2 within Nepal.

Since the second half of the 20th century, several glacial lakes have developed in the Poiqu basin. This may be attributed to the effect of recent global warming. The glaciers are retreating and the lakes are formed on the glacier terminus. Most of the glacial lakes are formed due to damming by unstable moraines. Lake outbursts release an enormous amount of stored water, which causes serious floods downstream along the river channel. This phenomenon, generally known as glacial lake outburst floods (GLOFs), is recognized as a common problem in Poiqu basin.

China carried out glacier inventory throughout the country from 1979. This work was completed in 2002 and documented in 21 books. In this glacier inventory did not undertook a systematic inventory of glacial lakes. A China-Nepal joint team carried out fieldwork in the Pumqu and Poiqu River basins and inventoried glaciers and glacial lakes in 1980s. They carried out research on the outburst of glacial lakes and published a book entitled “Report on the First Expedition to Glaciers and Glacier lakes in the Pumqu (Arun) and Poiqu (Bhote-Sun Koshi) River basins, Xizang (Tibet), China”.

Cold and Arid Regions Environmental and Engineering Research Institute of the Chinese Academy of Science and the Tibet Water Conservancy and Hydrology Bureau of China in collaboration with ICIMOD undertook the project entitled “Inventory of Glaciers and Glacial Lakes and Glacial Lake Outburst Floods’ Monitoring and Early Warning Systems in the Hindu Kush-Himalayan Region” from June 2002. Though there is the database of glaciers and glacial lakes of one time, this study is primarily based on the temporal satellite images of different dates from 1970s to recent to detect the activity of glaciers and glacial lakes. This study will help to understand the climate change and its impact on glaciers and glacial lakes and site selection for Early Warning Systems for the potential GLOF to reduce the hazard level.

1.2 RIVER SYSTEMS

The Poiqu River originates from the northwestern slope of Laptshegang Mountain. The highest elevation in this basin is 8012 masl at Xixiabangma and the lowest is 620 masl at the river outlet border to Nepal. In Nepal the river is named as SunKoshi – BhoteKoshi. The total length of river is 146 km in the study area, about 78km length lies within China and 68km within Nepal. There are 14 main tributaries; they are Korru Pu, Targyailing Pu, Tongpu, Poiqu, Sun Kosi, Balephi, Puma Pu, Zhang Zangbo, Congdui Pu, Koryag Pu, Gyaiyi Pu, Sunkoshi Nadi, Jia Pu, and Laza Pu. The length of the tributaries ranges from 9km to 52km and the longest tributary is Balephi in Nepal (Table 1.1 and Figure 1.2).

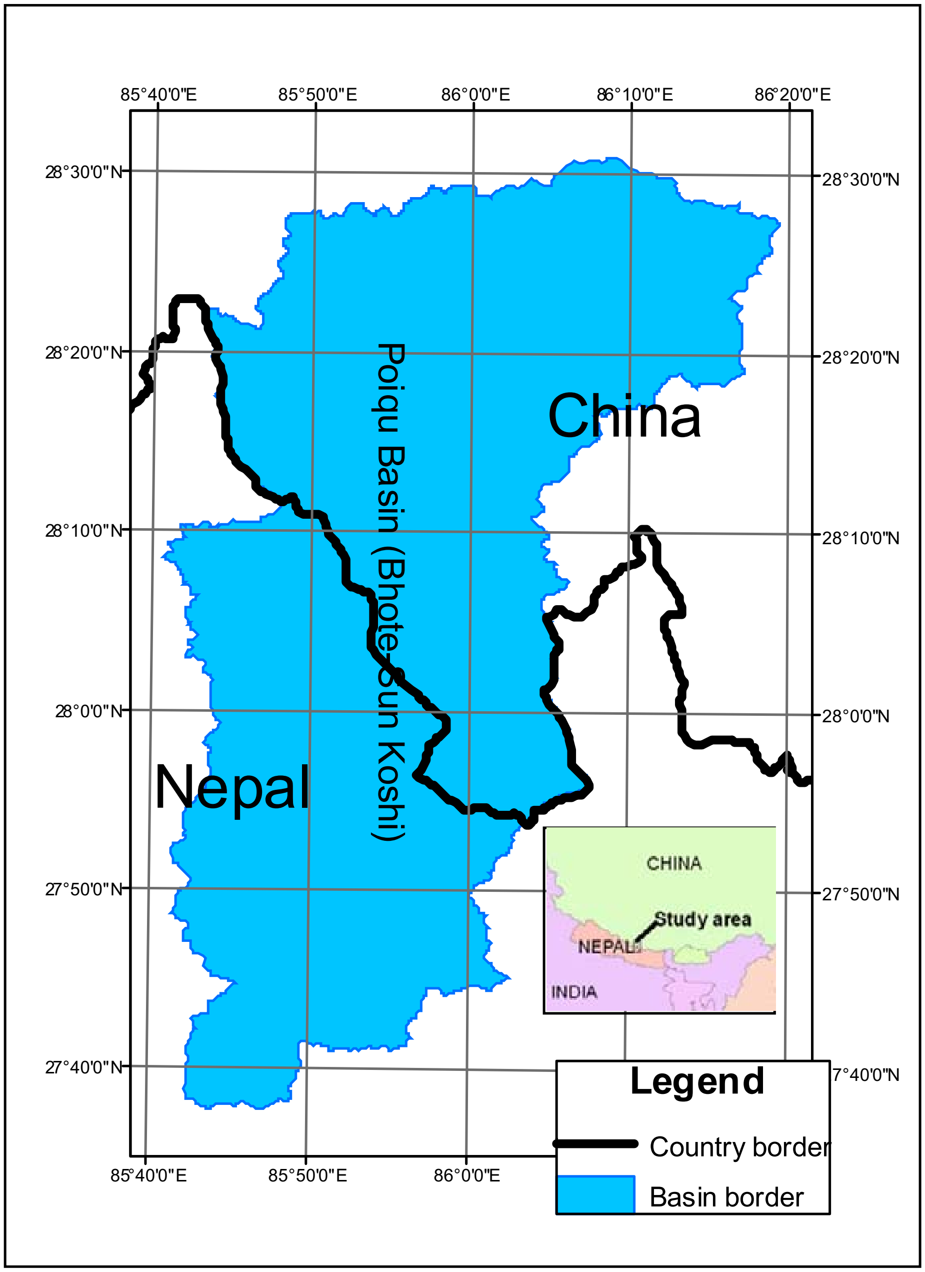


Figure 1.1: Poiqu (Sun Koshi- Bhote Koshi) River basin in China and Nepal
(Note: Country boundary shown in the maps is not authoritative)

1.3 HYDRO-METEOROLOGY

Poiqu basin is located on the leeward side of the Himalayan range, so the basin receives considerably less precipitation than the southern region of that range. Generally, the precipitation in the Tibet basin decreases from west to east and also from south to north.

Meteorological data such as temperature, rainfall, and evaporation of the Tibet part of Himalaya inChina region are available from the meteorological stations at Tingri from 1960 to 1987. The annual distribution of rainfall in the region is not uniform.

Table 1.1 Main Tributaries in the Poiqu (Bhote-Sun Koshi) River Basin			
S.No.	Name of Tributaries	Length (km)	Elevation differences (masl)
1.	Tongpu	29.6	5300 – 4400
2.	Laza Pu	13.9	5100 - 4400
3.	Gyaiyi Pu	23.3	5900 - 4300
4.	Koryag Pu	28.0	5160 - 3900
5.	Targyailing Pu	11.9	5380 - 4200
6.	Korru Pu	9.4	5180 - 3900
7.	Jia Pu	17.9	5100 - 3900
8.	Congdui Pu	24.6	5080 - 3800
9.	Zhang Zangbo	8.4	4870 - 3600
10.	Puma Pu	16.2	4600 - 1960
11.	Balephi	52.1	4500 - 700
12.	Sunkoshi Nadi	15.1	3240 - 910
13.	Poiqu	48.8	4300 - 2200
14.	Sun Kosi	59.7	2200 - 630

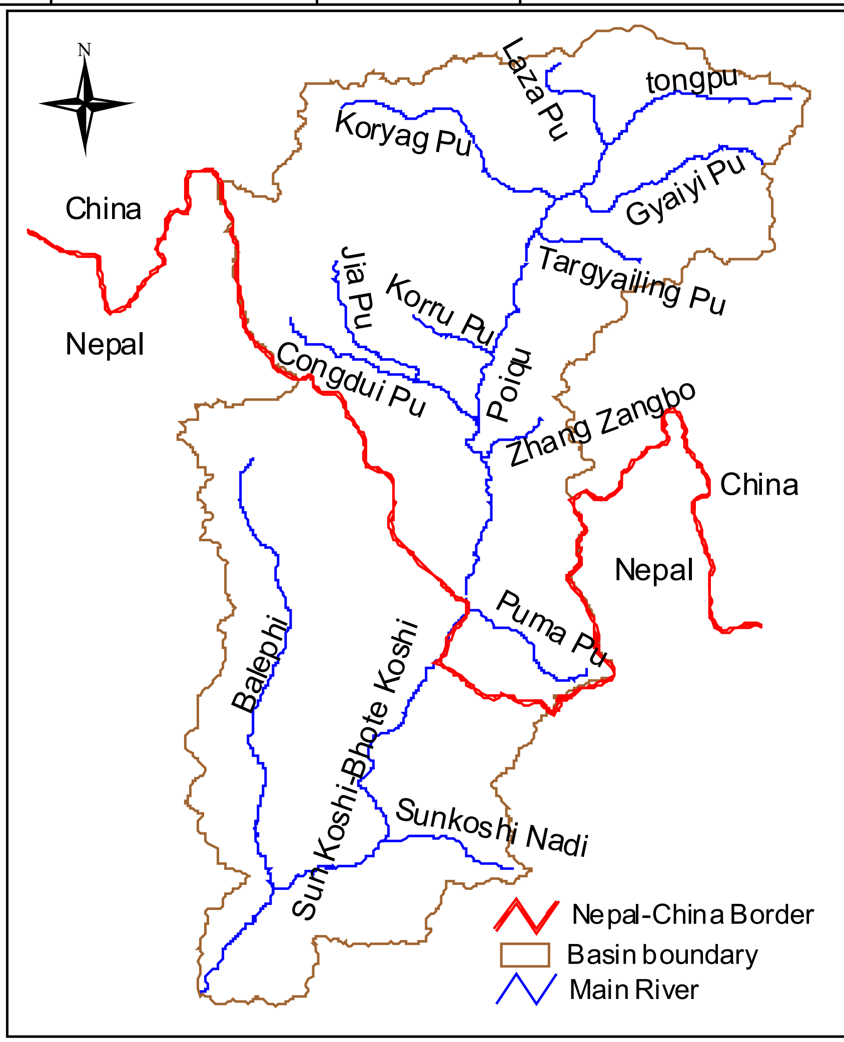


Figure 1.2 The Poiqu River and its tributaries
(Note: Country boundary shown in the maps is not authoritative)

Nielamu is only one meteorological station in Poiqu basin (1967s-2003). So, another station Tingri (shegar) close to Poiqu basin is taken as reference. The stations measure daily rainfall, daily maximum and minimum temperatures, relative humidity, wind speed, and evaporation, atmospheric pressure. Precipitation, air temperature, evaporation and relative humidity play an important role in the analysis of climate of the basin.

Air Temperature
The mean elevation of the Tibet part of Himalaya in China region is above 4,500 masl. Therefore, the annual mean air temperature is low because of the high altitude. These years, with the global warming, the atmosphere environment has changed. The increase in temperature can have an impact on the condition of glaciers; higher temperature can cause rapid melting of glacier ice. Now many people pay close attention to the urgent problem, that is snowline is shifted at higher elevation and water level of the glacial lakes is changing. Mean annual temperature from 1971 to 2000 at Nie Lamu station shows a clear increase in temperature after 1990s (Figure 1.3). The trends are accelerated after 1998. The Poiqu River basin belongs to semi-humid region. The Nielamu meteorological station shows the annual mean temperature is 3.5° and the lowest mean temperature is -3.7°, which occurred in January. The highest mean temperature is 10.4°, which occurred in July. The highest temperature is 22.4° and the lowest one is -20.6°. The annual mean temperature at Tingri is 2.7 degrees centigrade and the extreme mean monthly temperature from 1970 to1999 ranged from -9.9 to 13.2°C. From November to March, the temperature falls gradually below zero. The variation of air temperature from year to year is small, but the diurnal variation of the temperature is very large. The temperature data of Tingri station shows the warming trend (Figure 1.3).

Precipitation
The Poiqu River valley is the main vapor passage. The major source of precipitation is from the warm-moist monsoon air from the southwest. The precipitation decreases from south to north gradually. The annual precipitation is 2817mm at Zham (Khasa) District in the southern edge of the Poiqu River valley and reduces to 666 mm at Nyalam. It is estimated that there may be an annual precipitation of 300-400 mm at the northeast edge of the basin. Precipitation in the Poiqu River basin from June to September constitutes 51-53% of annual precipitation. On the other hand, due to the presence of the Himalayan Range, the warm-moist air generally follows the river valleys and so does the precipitation. Hence precipitation at the lower reaches of the basin is comparatively higher. In general, due to the barrier effect of the mountains the annual mean precipitation decreases with the increase of altitude.

Through analysis for the precipitation data of Nielamu station: annual mean precipitation is 650mm; maximal four months precipitation, which is about 47% of the annual volume occurs from June to September. There is so much snow and rainfall in winter and the rainfall season starts early in this area, so precipitation is uniform distribution in a year and smaller changing every year.

Through analysis for the precipitation data of Tingri station which in northwest of the basin: annual mean precipitation is 265mm; precipitation maximum which is about 50% of the annual volume generally occurs in July or August maximal four months precipitation which is about 94.2% of the annual volume occurs from June to September precipitation is uneven distribution in a year and smaller changing every year annual precipitation in the wettest year is 4.5 times that of the driest year.

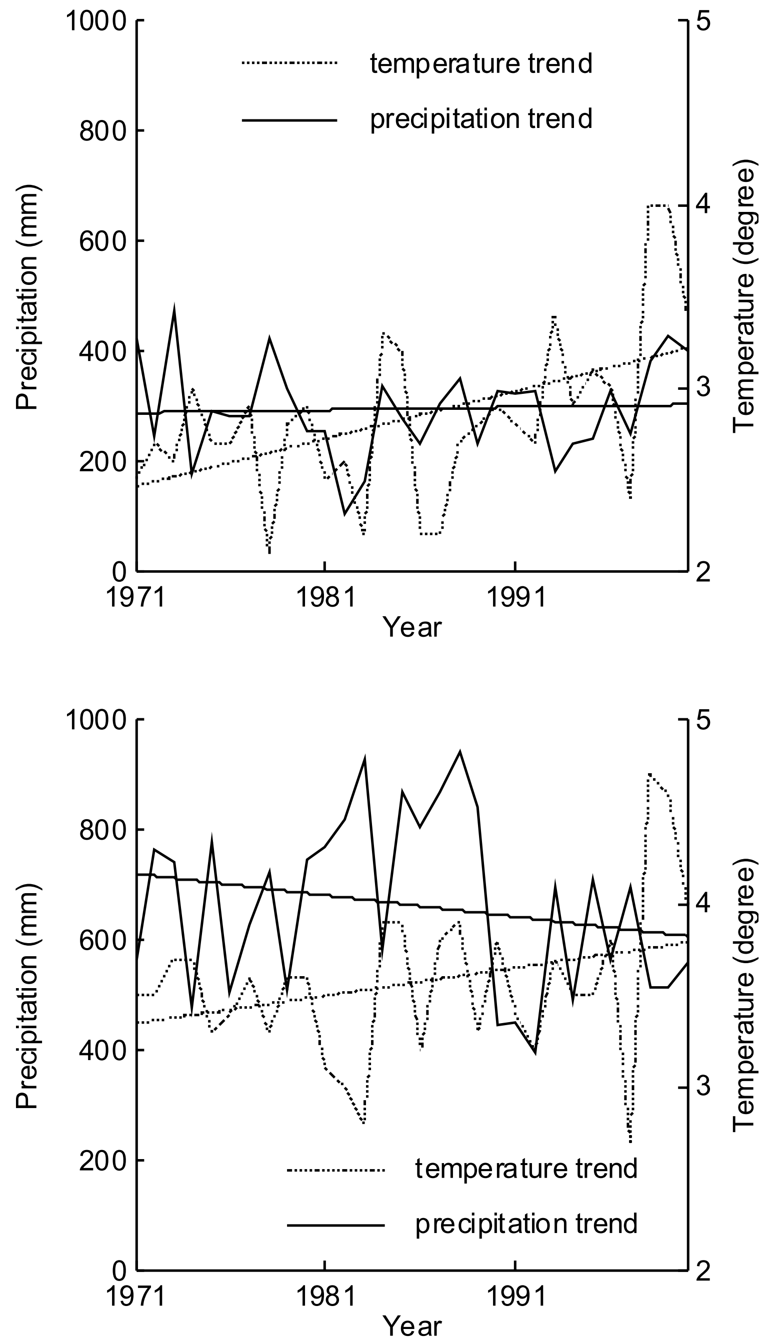


Figure 1.3 Mean annual temperature and precipitation from 1971 to 2000 at Tingri station (bottom) and Nie Lamu station (top)

The Cv value of precipitation in this region is between 0.20-0.30. Consecutive dry years or wet years occurred in the area.

Evaporation
Evaporation is extremely high due to strong wind, high solar radiation, and low humidity. The annual mean evaporation (1971-1980) observed at Tingri is 2,553mm. The highest evaporation rate occurs in the months of May and June and the lowest in December and January. The annual evaporation at Chentang, the lower reaches of the Pumqu River basin near the Nepal/China boarder, is estimated at about 1,000mm. The evaporation increase from south to north: La zi is 2800mm, Tingri is 2550mm, and Nie lamu is 1600mm. There is no more changing for every year; Maximum annual evaporation is less than 1.5 times that of the minimum value.

River discharge
Major rivers in Tibet part of Himalaya in China region originate from glaciers. Glaciers and seasonal snow area is about 25%. The supply to runoff contributed from groundwater mix with snowmelt and precipitation. Annual mean runoff is about $50*10^8$ m^3.

Here is an analysis for La zi hydrological station, that maximum discharge is $1390m^3/s$ (1999), minimum discharge is $25.9m^3/s$ (1992), the timing of discharge coincide closely with seasonal maximum and minimum of precipitation at basin scales, discharge maximum generally occurs in August coinciding with the peak of the monsoon, minimum values occurs during the months of December-January, maximal four months discharge which is about 66.1% of the annual volume that occurs from June to September, discharge is uneven distribution in a year and smaller changing every year, annual maximum in a year is 2.7 times that of the minimum value (Figure 1.4).

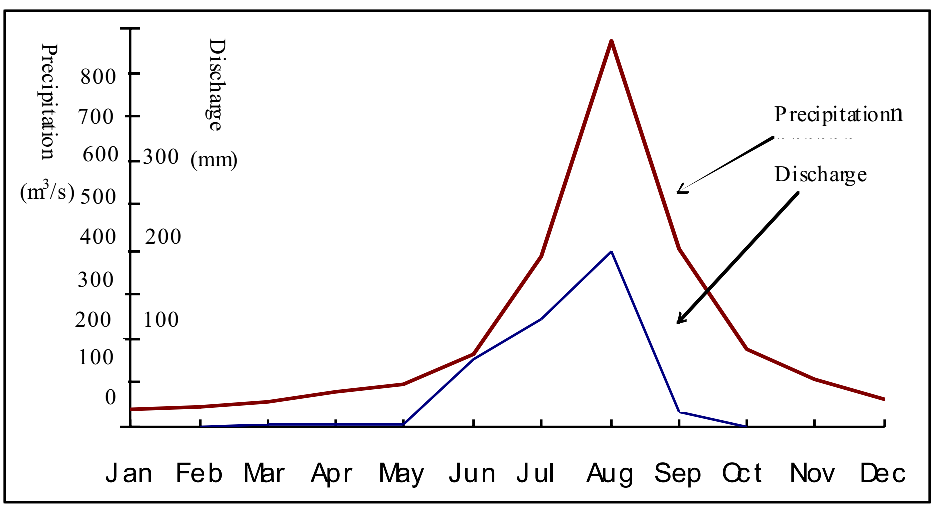
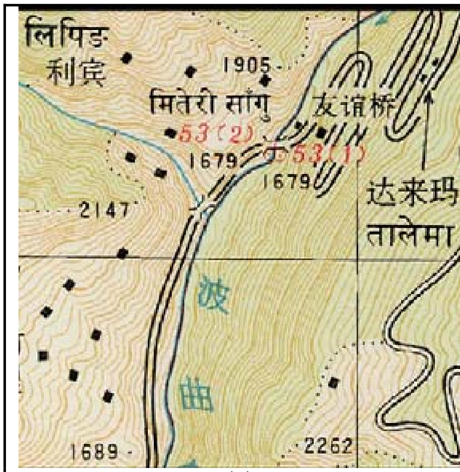


Figure 1.4: Hydrograph of discharge and precipitation from La zi station

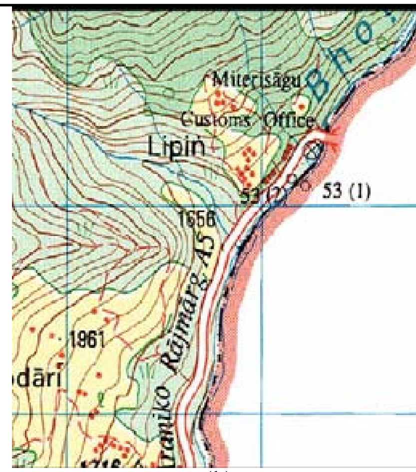
1.4 MATERIALS

The study is mainly based on Remote Sensing (RS) and Geographic Information (GIS) data. Different types of satellite images of several dates from 1970s to 2003, large-scale topographic maps and aerial photographs were used.

The topographic maps published by the survey of China, Nepal and India (Figure 1.5) at the scale of 1:50,000 and 1:63,360 were used for the reference and to obtain some attributes of glaciers and glacial lakes. The elevation, position and name of village, river, and bridge in the Basin identified from the topographic maps. The combination of digital satellite data and the Digital Elevation Model (DEM) is also used for better and more accurate results (Figure 1.6).



(a)



(b)

(a)

Figure 1.5 A portion of the Topographic maps around the friendship bridge area at Nepal and China border.

(a) Published in 1979 by Survey of China. Scale is 1: 50,000

(b) Published in 1996 by Survey of Nepal. Scale is 1: 50,000.

(c) Published in 1958 by Survey of India. Scale is 1: 63360

The satellite data includes Landsat MSS of 1977 and 1984, MOS image of 1988, Landsat TM of 1990, and 1996, IRS 1D-LISS 3 image of 2000 and 2001, Landsat ETM+ of 2001 and EOS ASTER images of 2003 (Figure 1.7). The spatial distribution and shape of glaciers and glacial lakes was identified and digitized from the images and compared for the activity analysis of the glaciers, glacial lakes and identification of potentially dangerous glacial lakes. Various types of satellite image suitable for the present study are available from ICIMOD archives, global land cover facility (http://www.glcf.org) and the EOS ASTER images from the GLIMS (http://www.glims.org).

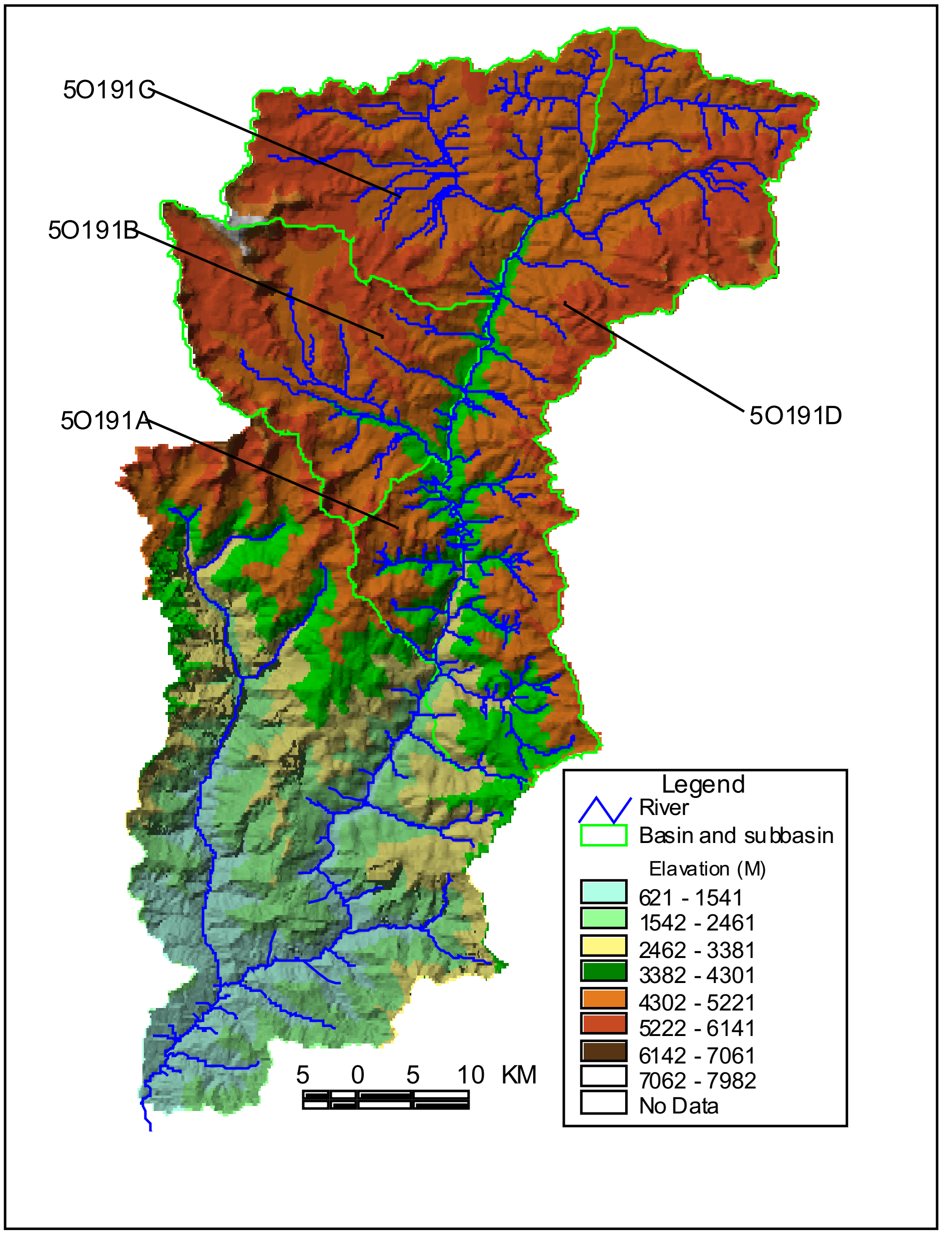


Figure 1.6 Digital Elevation Model (DEM) and sub-basins of Poiqu basin
(Note: Country boundary shown in the maps is not authoritative)

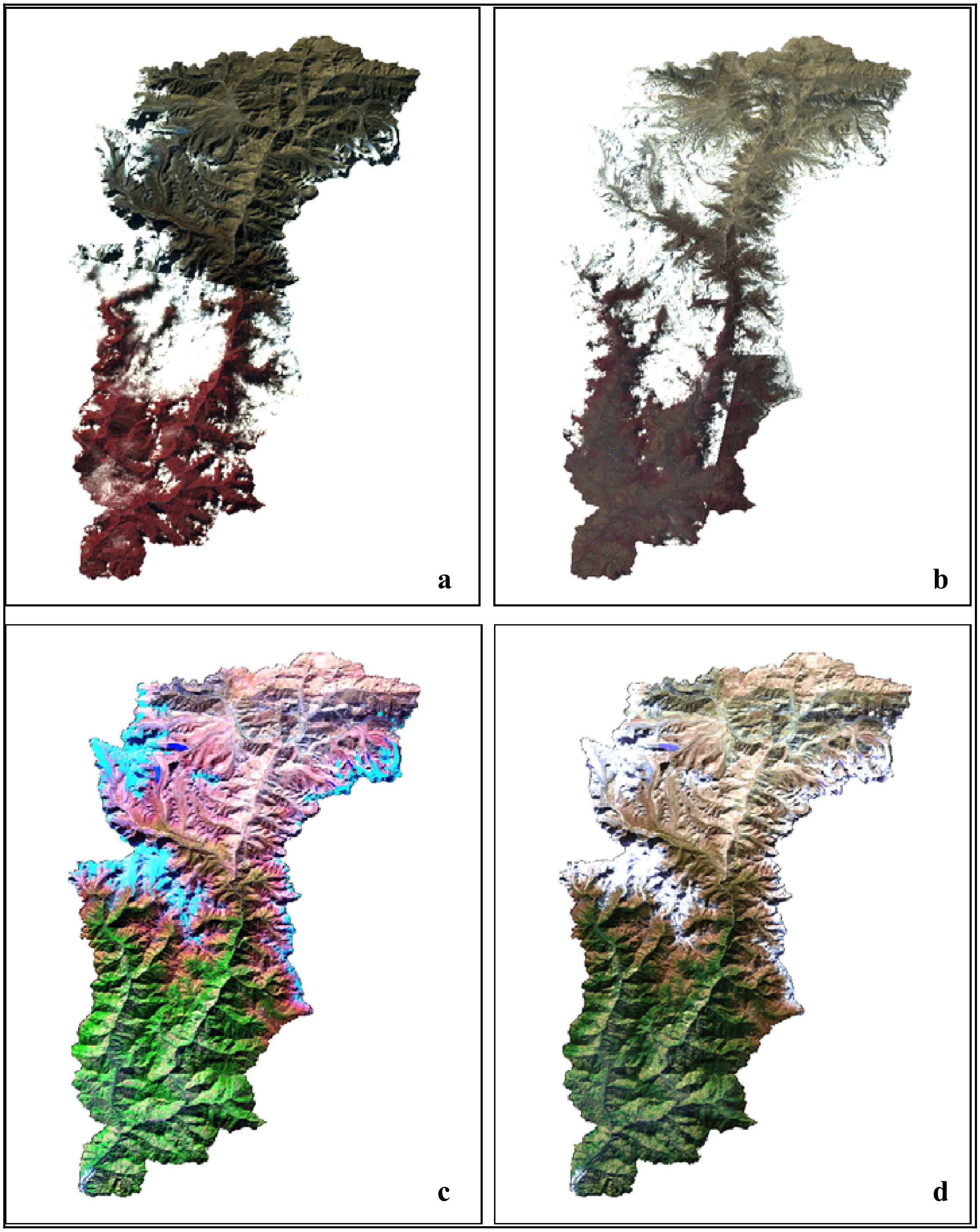


Figure 1.7: Satellite images of Poiqu Basin: (a) MSS of 1970s; (b) MSS of 1980s; (c) TM of 1990s and (d) ETM+ of 2000s.

2 GLACIERS

The methodology for the mapping and inventory of the glaciers is based on instructions for compilation and assemblage of data for the World Glacier Inventory (WGI), developed by the Temporary Technical Secretary (TTS) at the Swiss Federal Institute of Technology, Zurich (Muller et al. 1977). This methodology is used in the inventory of glaciers of Hindu Kush-Himalayan (HKH) region by ICIMOD (LIGG/WECS/NEA 1988; Mool et al 2001a, 2001b; Wu Lizong et al. 2004, 2005;)

2.1 Glaciers in 1988

The inventory of glaciers was carried out from the topographic maps published in 1979. For the inventory the basin is divided into four sub-basins 5O191A, 5O191B, 5O191C, and 5O191D (Figure 1.6). According to the glacier inventory of 1988, there are 153 glaciers in the Poiqu River basin with an area of 243.86 km^2 and an estimated ice reserve of 20.30 km^3 (Table 2.1 and Figure 2.1).

Table 2.1: The glacier in the Poiqu basin (Bhote Koshi – Sun Koshi) in the 1988

Sub-basin	Glacier Number	Number (%)	Area of glacier (km^2)	Area (%)	Ice Reserve (km^3)	Reserve (%)
5O191A	19	12.42	12.68	5.20	0.57	2.81
5O191B	35	22.88	112.03	45.94	10.84	53.40
5O191C	30	19.61	47.93	19.65	4.51	22.21
5O191D	69	45.10	71.22	29.21	4.38	21.58
TOTAL	153	100	243.86	100	20.30	100

The characteristics of the Himalayan glaciers are mostly smaller in size. For example, the small glaciers (Area< 1km^2) contribute more than 70 % in the total number of glaciers but only about 19 % of the total glacier area (Table 2.2). The highest number of glaciers is contributed by the size 0.1-0.5 sq km and maximum area contributed by the larger size glaciers. Though the small size glaciers are high in number and large size glaciers are smaller in number but the area and ice reserve are contributed high by the large size glaciers.

Table 2.2: Glacier characteristics classified by different area classes in 1988

Glacier Size (km^2)	Number		Area (km^2)	
	Number	%	Total	%
<0.1	9	5.88	0.58	0.24
0.1-<0.5	69	45.10	17.83	7.50
0.5-<1.0	36	23.53	26.02	10.94
1.0-<5.0	25	16.34	46.88	19.71
5.0-<10	10	6.54	67.17	25.72
10-<20	1	0.65	10.66	4.48
>20	3	1.96	74.70	31.41
Total	153	100.00	243.86	100

2.2 Glaciers in 2000

For the delineation of glaciers the IRS 1D-LISS satellite images of 2000/2001 were used by co-registering with reference to the topographical maps and the MOS satellite image. Altogether 151 glaciers covering an area of 231.58 km^2 with an ice reserve of approximately 19.03 km^3 in the Poiqu basin. The Distribution of glaciers in each sub-basin is shown in the Figure 2.1 and Table 2.3.

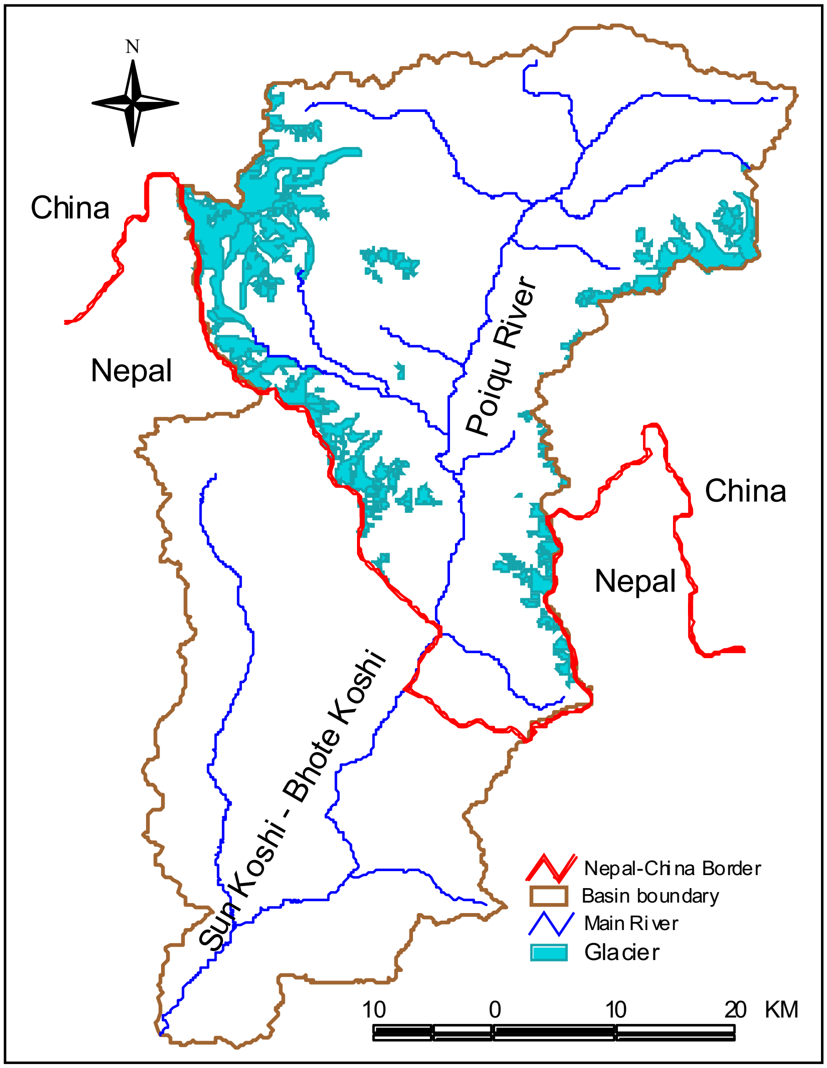


Figure 2.1 Distribution of Glaciers in the Poiqu basin
(Note: Country boundary shown in the maps is not authoritative)

Table 2.3: Glacier in Poiqu Basin (Sun Koshi-Bhote Koshi) in 2000/2001

Sub-basin	Glacier Number		Area of glacier		Ice Reserve	
	Number	(%)	(km^2)	(%)	(km^3)	(%)
5O191A	19	12.58	11.96	5.16	0.49	2.57
5O191B	37	24.50	109.03	47.08	10.30	54.16
5O191C	27	17.88	47.04	20.31	4.44	23.33
5O191D	68	45.03	63.55	27.44	3.79	19.94
TOTAL	151	100.00	231.58	100.00	19.03	100.00

2.3 Change analysis of Glaciers from 1988 to 2000

For the demonstration of the change and analysis of glacier, the database of glaciers of 1988 and 2000 were used. The database of glaciers of 1988 was based on the MOS satellite image and glaciers of 2000 was based on 3 satellite images of IRS 1D-LISS 3. This database obtained from the satellite images were verified in 1:50,000 and 1:100,000 scale topographic maps published in 1980s. Glacier changes from the 1988 to 2000/2001 in the four sub-basins are given in Table 2.4.

Table 2.4: The glacier change of each sub-basins of Poiqu River

Sub-basin	Glacier Number			Area of Glacier (Km^2)			Ice Reserve (Km^3)		
	1988	2000	Change %	1988	2000	Change %	1988	2000	Change %
5O191A	19	19	0.00	12.68	11.96	-5.68	0.57	0.49	-14.04
5O191B	35	37	+5.71	112.03	109.03	-2.68	10.84	10.30	-4.89
5O191C	30	27	-10.00	47.93	47.04	-1.86	4.50	4.45	-1.11
5O191D	69	68	-1.45	71.22	63.55	-10.77	4.38	3.79	-13.47
TOTAL	153	151	-1.31	243.86	231.58	-5.04	20.30	19.03	-6.26

During the retreat of glaciers, some of the glaciers are lost, breakdown and submerged. So the total number of glaciers in the sub-basins are slightly changed and but in total 2 glaciers are reduced in number. The change in number is not the crucial but the change in area indicates the direct impact of glacier retreat and advances. The percentage of area change in different periods was calculated as the ratio of the total decrease in area to the total area in the 1988 before area changes occurred. For example, the percentage of area change from the 1988 to 2000 are taken as $(S_{1988} - S_{2000})/S_{1988}$.

During the 1988, the total area of all 153 measured glaciers was 243.86 km^2, whereas the total area in 2000 is 231.58 km^2. The difference of area is 12.28 km^2 decreased by 5.04% and volume by 1.40% from the 1988 to 2000. The decrease was the greatest (-10.77%) in the **5O191D** sub-basin, and second largest (-5.68%) in the **5O191A** sub-basin. The least change occurred in the **5O191C** sub-basin, where the average decrease was only **-1.86%**. The greatest shrinkage 14.04% in volume is in the **5O191A** sub-basin.

The comparative study of glaciers from 1988 to 2000 shows that the glaciers are retreating and the ice reserve is shrinking. With the retreat of glaciers, rapid melting of glacier ice and snow can result in the rise of glacier lake level, which then becomes vulnerable to GLOF.

3 GLACIAL LAKES

The methodology for the inventory of glacial lakes is base on that developed by the Lanzhou Institute of Glaciology and Geocryology, the Water and Energy Commission Secretariat, and the Nepal Electricity Authority (LIGG/WECS/NEA, 1988 and Mool et al 2001a)

3.1 Glacial Lakes in 1980s

According to the statistics of 1988, there are 45 glacial lakes with an area of 12.312 km^2 in the Poiqu basin. In fact, based on the MOS images in 1988, there are some small glacial lakes were neglected in the inventory of 1987 (LIGG/WECS/NEA 1988). In total, there are 119 glacial lakes in the Poiqu basin with the area of 13.42 km^2 (Figure 3.1).

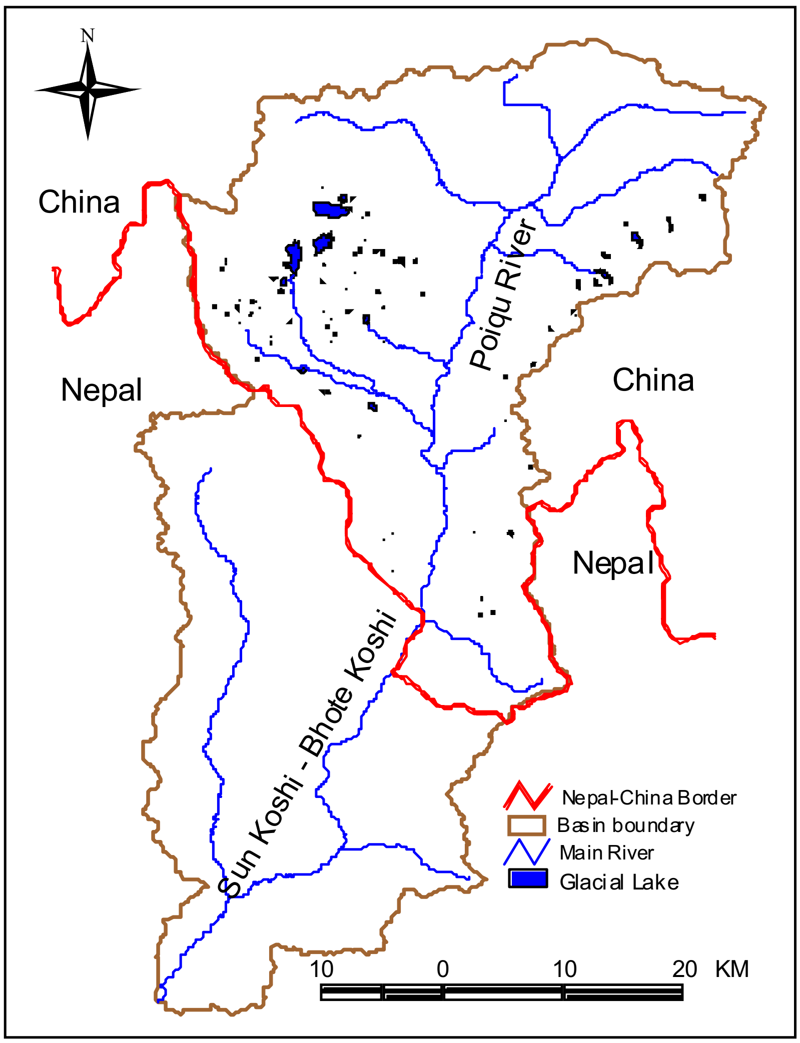


Figure 3.1 Distribution of Glacial Lakes in Poiqu basin
(Note: Country boundary shown in the maps is not authoritative)

3.2 Glacial Lakes in 2000

The study of lakes in 2000 revealed 139 lakes in the Poiqu basin with the total area 16.39 sq. km. There are cirque lakes, end moraine dammed lakes, trough valley lakes, and blocking lakes. Among them the largest number and area are associated with end moraine-dammed lakes. This kind of lakes normally develops in the inner side of moraine ridges of the Little Ice Age, not far from their associated mother glaciers.

Exceptionally, valley lakes are higher in number (74) and then moraine dammed lakes (59) (Table 3.1). There are only 6 Cirque lakes. Comparatively erosion lakes, cirque lakes, and valley lakes are not potentially dangerous as they are isolated and not associated with the hanging glaciers.

Table 3.1: Types of lakes in the Poiqu River basin

Type	Number	Number (%)	Area (km^2)	Area (%)	Area of largest lake (km^2)
Valley	74	53.24	2.84	17.33	0.48
Cirque	6	4.32	2.68	16.33	2.33
Moraine dammed	59	42.44	10.87	66.34	3.62
Total	139	100.00	16.39	100	6.43

3.3 The glacial lake change

Based on the two inventories in 1980s and 2000s, the general change in every sub-basin can be easily found from the Table 3.2. The typical glacial lakes like LumuChimi and GangxiCo were analysed in more detail with the help of images (Landsat MSS, TM, ETM+ and EOS ASTER) from 1970s to 2000s. Furthermore, the analysis of typical glacial lakes can obtain the detail change trend just like the glacier change analysis. The detail results of glacial lakes will be considered as the basic information for the identification of dangerous lake.

Table 3.2: The glacial lake change of each sub-basin

Sub-basin Name	Number of Lakes			Area(km^2)		
	In 1980s	In 2000s	%	In 1980s	In 2000s	%
5o191A	3	3	+0.00	0.08	0.09	+11.25
5o191B	64	74	+15.63	7.07	8.21	+16.18
5o191C	21	24	+14.29	3.69	4.83	+30.96
5o191D	31	38	+22.58	2.58	3.26	+26.16
Total	119	139	+16.81	13.42	16.39	+22.14

4 Potentially Dangerous Glacial Lakes

Based on the analysis of inventory data using different criteria and the study of satellite images, 9 glacial lakes are identified as potentially dangerous lakes in the Poiqu basin. The identified potentially dangerous lakes are recommended for further detailed investigation and field survey to understand their activity (Figure 5.1 and Table 4.1).

Table 4.1: Potentially dangerous glacial lakes in the Poiqu River basin

Lake number	Lake name	Latitude	Longitude	Altitude (masl)	Length (km)	Area (km^2)
5O191B0030	LumuChimi	28°19.23'	85°50.49'	5100	2.8	3.84
5O191C0011	GangxiCo	28°21.49'	85°53.72'	5220	2.7	3.64
5O191D0001		28°22.42'	86°16.59'	5610	0.5	0.19
5O191D0002		28°21.80'	86°14.61'	5500	1.0	0.44
5O191D0007		28°20.11'	86°12.57'	5500	1.4	0.61
5O191D0008	Gang Puco	28°19.22'	86°10.56'	5580	0.8	0.24
5O191D0009	Paqu Co	28°18.28'	86°09.45'	5330	1.8	0.62
5O191D0011	Tara Co	28°18.81'	86°08.92'	5240	1.0	0.26
5O191D0025	Zhangzangbo	28°04.09'	86°04.88'	5200	0.8	0.20

5 THE SITES SELECTION FOR THE EARLY WARNING SYSTEM

After the inventory of glacier and glacial lake the typical glaciers and glacial lakes were analysis by the multi-temporal remote sensing images and GIS in detail. Nine dangerous lakes have been identified according to the change of glaciers and glacial lakes. These glacial lakes posed a potential glacial lake outburst floods (GLOFs) in future. To reduce the hazard from the GLOF the potentially dangerous glacial lakes should be monitored in regular basis and detail fieldwork should be carried out. To save the life and property before the mitigation work Early Warning Systems are recommended.

Ten sites for Early Warning Systems (EWS) have been proposed in the Poiqu basin (Sun Koshi - Bhote Koshi). The Figure 5.1 shows the location of proposed sites of Early Warning Systems along the downstream of potentially dangerous glacial lakes, while some detail information can be found in the Table 5.1. The associated dangerous lakes have been marked for every site (Table 5.1).

Table 5.1 The information about the sites selected for Early Warning System (EWS)

ID	Description	Lon	Lat	Elevation	River/Stream	Distance[1] (km)
1	Below Ta Shakan	86.02	28.28	4058	Poiqu River	62.3
2	Congdui	85.98	28.15	3840	Poiqu River	20.9
3	along Jia Pu	85.84	28.27	4975	Jia Pu	44.2
4	along Koryapu	85.99	28.39	4377	Koryag Pu	80.7
5	between Yali and Tashakan	86.09	28.36	4339	Gyaiyi Pu	75.4
6	below Chuhsiang	86.00	28.07	3212	Poiqu River	10.5
7	Near Zhangmu	85.97	28.01	2444	Poiqu River	2.4
8	Friendship Bridge	85.98	27.99	1964	Sun Kosi	0
9	Panlan	85.88	27.88	1495	Sun Kosi	16.9
10	Dolalghat	85.71	27.64	627	Sun Kosi	59.6

Note: Distance[1] means the distance of Site to the Friendship Bridge along the river channel.

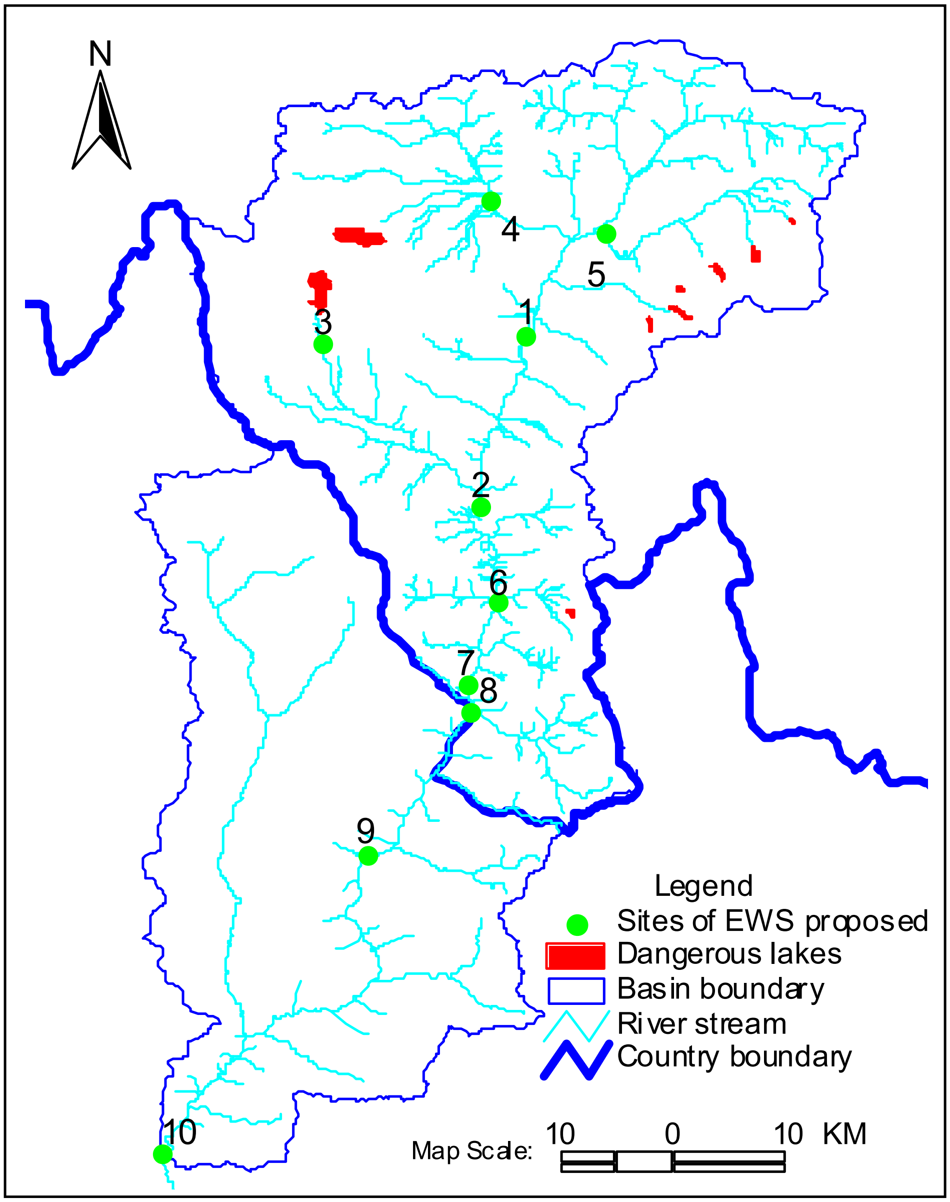


Figure 5.1 Locations of potentially dangerous glacial lakes and proposed Early Warning Systems (EWS)
(Note: Country boundary shown in the maps is not authoritative)

Table 5.2 shows the Early Warning Systems sites from 1 to 10 and the potentially dangerous glacial lakes. At least one site monitored one lake and as the site 6 to 10 are located at the low level which can monitor the GLOF from all 9 potentially dangerous glacial lakes.

Table 5.2 The associated dangerous lakes at these sites

LAKE ID of potential dangerous lakes	EWS SITE ID									
	1	2	3	4	5	6	7	8	9	10
5O191B0030		Y	Y			Y	Y	Y	Y	Y
5O191C0011	Y	Y		Y		Y	Y	Y	Y	Y
5O191D0001	Y	Y			Y	Y	Y	Y	Y	Y
5O191D0002	Y	Y			Y	Y	Y	Y	Y	Y
5O191D0007	Y	Y			Y	Y	Y	Y	Y	Y
5O191D0008	Y	Y			Y	Y	Y	Y	Y	Y
5O191D0009	Y	Y				Y	Y	Y	Y	Y
5O191D0011	Y	Y				Y	Y	Y	Y	Y
5O191D0025						Y	Y	Y	Y	Y

Note: the Y means that the site can monitor GLOF from the potential dangerous glacial lakes.

6 Monitoring of selected Glaciers

As a case study two glaciers from the eastern slope of the Xixiabangma Mountain and five glaciers from the northern slope of the Laptshegang Mountain are taken for the monitoring with the help of different satellite images.

6.1 Two Glaciers on the Eastern slope of the Xixiabangma Mountain

To understand the glacier retreat in the basin two large glaciers (5O191B0029 in the 5O191B sub-basin, and the other one is 5O191C0009 in the 5O191C sub-basin) from the eastern slope of Xixiabangma Mountain are selected for the monitoring. MSS images of 1977 and 1984, the TM images of 1990 and 1996, ETM+ images of 2000 and ASTER images of 2003 were used (Figure 6.2).

From interpretation of images, the glacier change is obtained. The results of change analysis clearly show that the glaciers retreated from 1977 to 2003 significantly (Figure 6.1). The changes of glacier area and length are listed in the Table 6.1. The glacier area is reduced by 1.47 km^2 and 1.58 km^2 that accounts for 7.29% and 22.90% of the area in 1977 for the glacier 5O191B0029 and 5O191C0009, respectively. Similarly, the glacier length has receded by 1.22 km and 1.84 km from 1977.

The 5O191B0029 and 5O191C0009 glaciers decreased by 0.055 km^2 and 0.059 km^2 in area respectively per year since 1977. Similarly the length of the glaciers 5O191B0029 and 5O191C0009 retreated 45 m and 68 m in length per year since 1977.

The change trends of these two glaciers were illustrated in Figure 6.3 and 6.4. By a simple linear regress equation, the average change of glacier in past 27 years can be estimated just like the equation shown in Figure 6.3 and 6.4. The further change will be dominated by the glaciology, climate change and other geomorphic characteristics.

Table 6.1 The change statistic of glaciers on the East slope of Xixiabangma Mountain				
Date (yyyy-mm-dd)	5O191B0029		5O191C0009	
	Area(km^2)	Length(km)	Area(km^2)	Length(km)
1977-01-01	20.28	7.38	6.92	6.70
1984-04-09	20.09	7.12	6.68	6.32
1990-12-21	19.76	6.84	6.21	5.83
1996-10-18	19.40	6.51	5.83	5.41
2000-11-22	19.04	6.26	5.47	5.06
2003-12-05	18.81	6.16	5.34	4.86
Difference in 1977 and 2003	1.47	1.22	1.58	1.84

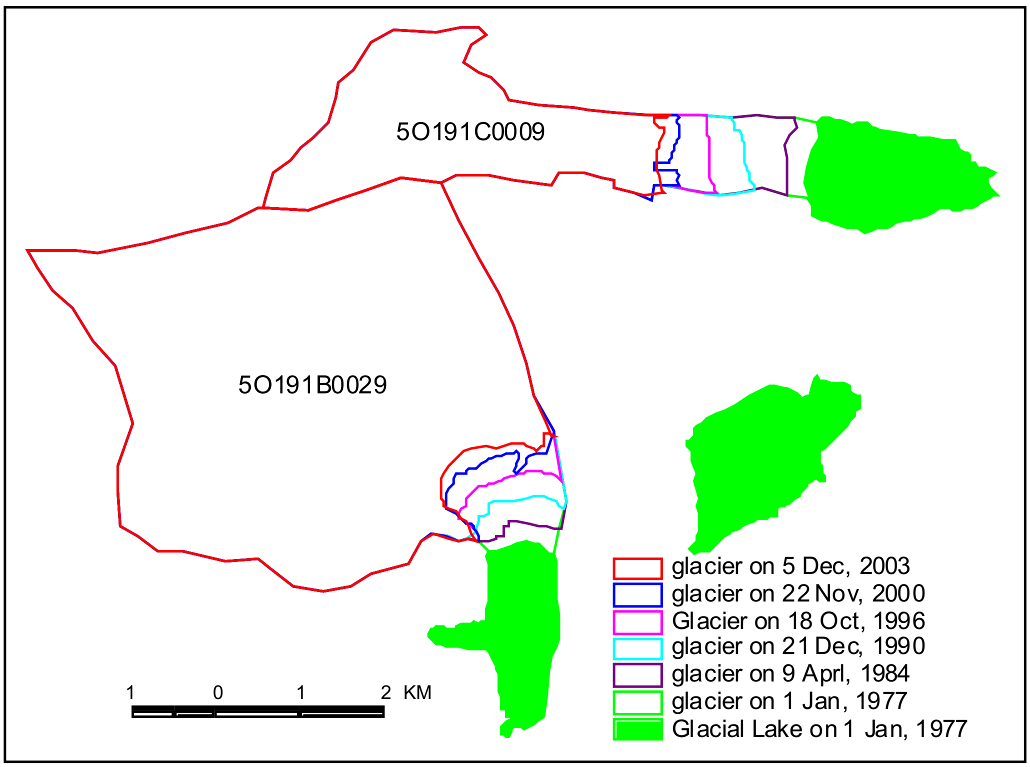
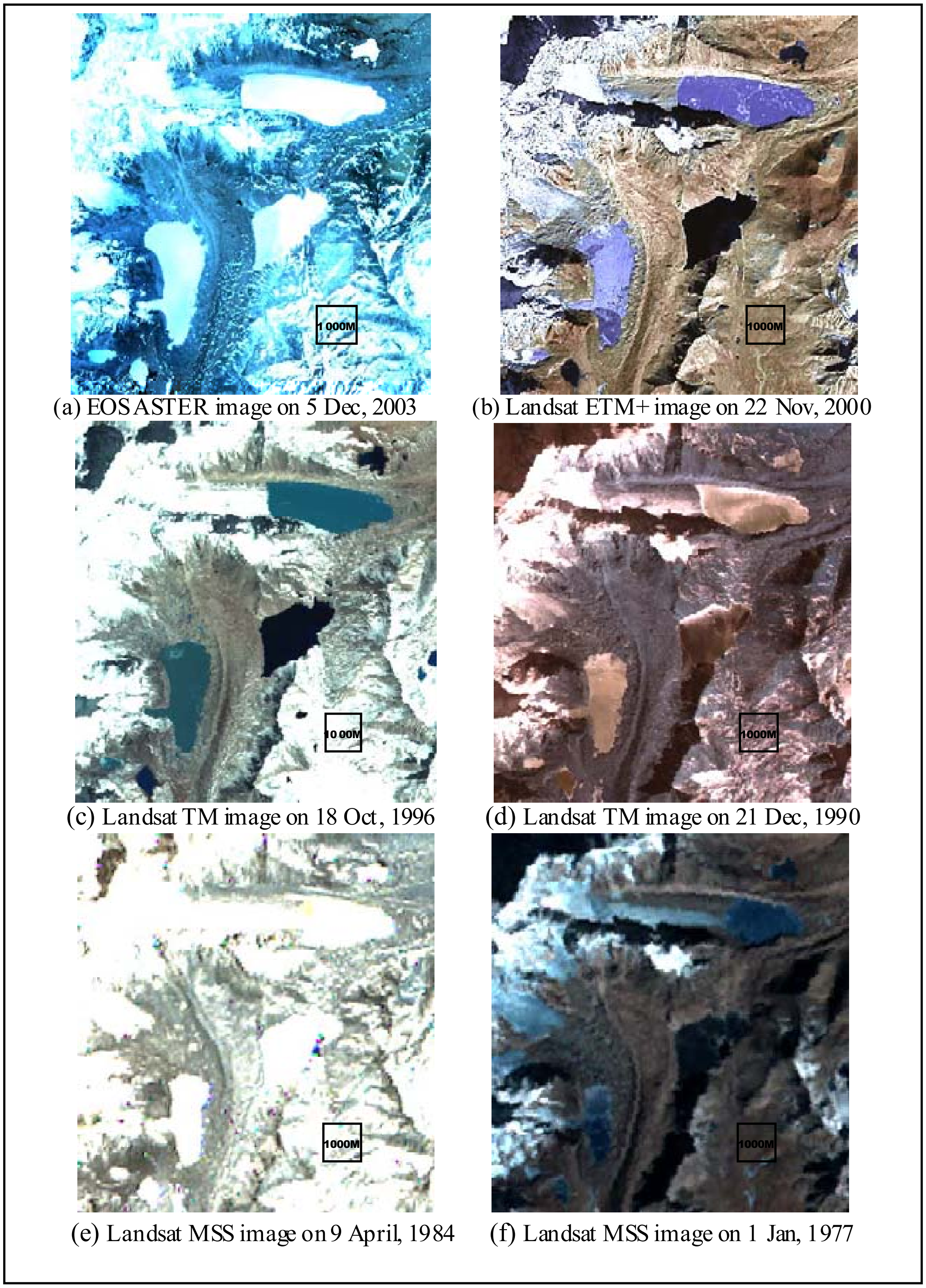


Figure 6.1 The change map of 5O191B0029 and 5O191C0009 glaciers on the eastern slope of Xixiabangma Mountain



(a) EOS ASTER image on 5 Dec, 2003

(b) Landsat ETM+ image on 22 Nov, 2000

(c) Landsat TM image on 18 Oct, 1996

(d) Landsat TM image on 21 Dec, 1990

(e) Landsat MSS image on 9 April, 1984

(f) Landsat MSS image on 1 Jan, 1977

Figure 6.2 Subsets of multi-temporal satellite images of the eastern slope of Xixiabangma Mountain showing 5O191B0029 and 5O191C0009 glaciers and GangxiCo and LumuChimi glacial lakes

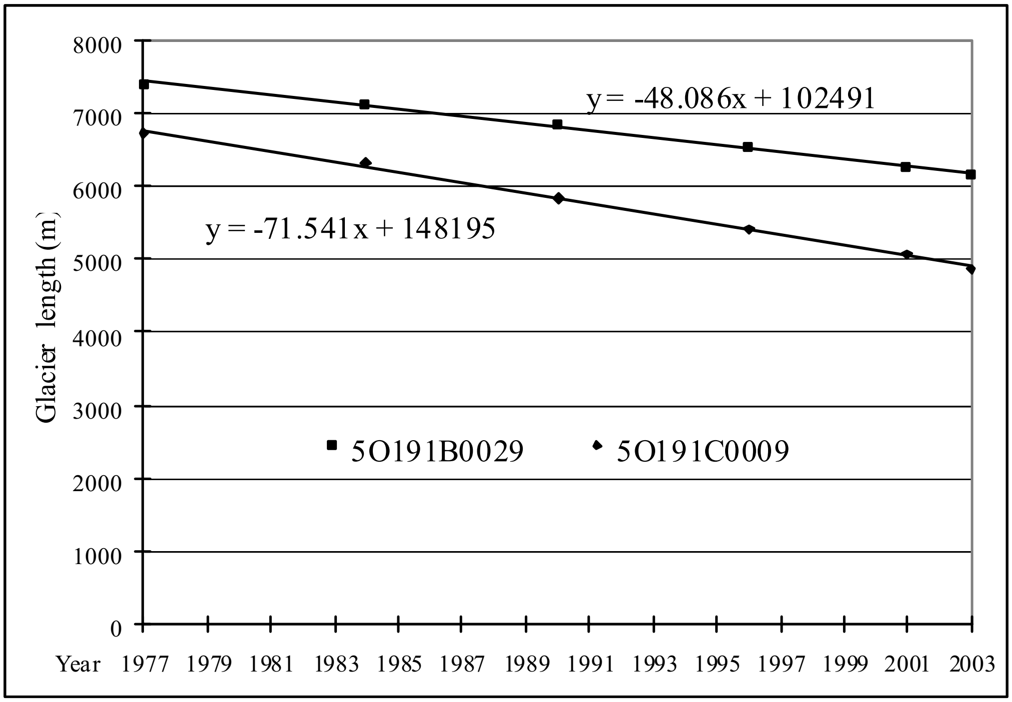


Figure 6.3 The change trend of glacier length

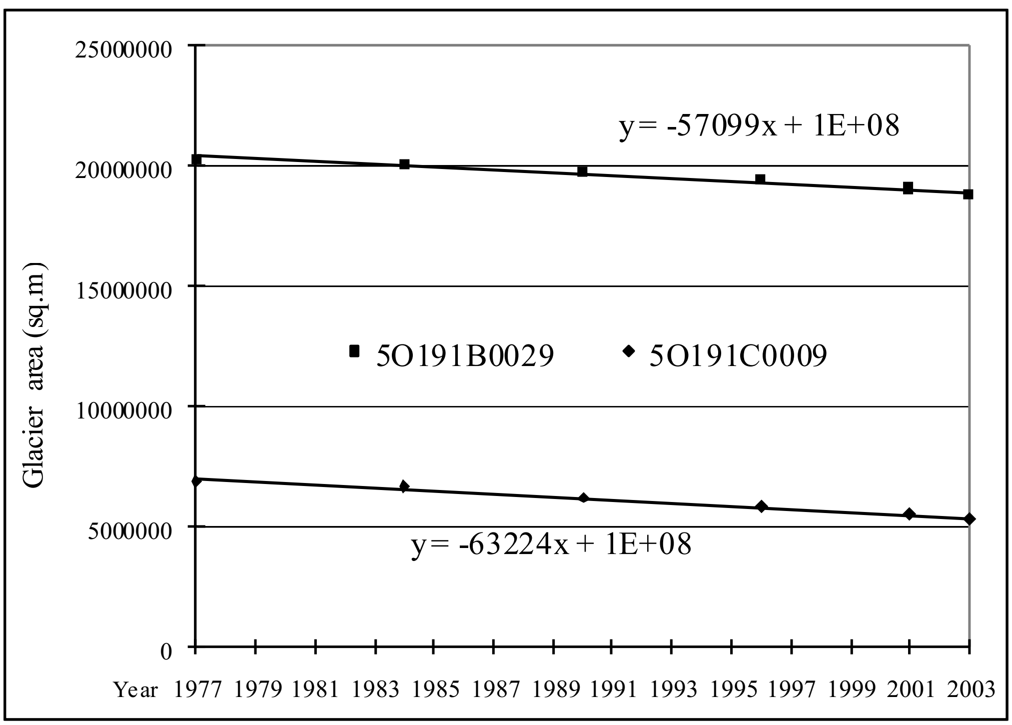


Figure 6.4 The change trend of glacier area

6.2 Five glaciers on the northern slope of the Laptshegang Mountain

The northern slope of the Lapsshegang Mountain also has several glaciers and glacial lakes. Five glaciers were selected for the demonstration of change mapping and analysis. Glaciers 5O191D0021 and 5O191D0024 are difficult to interpret from the images since 1996 because the ice within its tongue part always is shaded by the steep ridge and slope.

Due to the influence of seasonal snow cover, the Landsat MSS image in 1984 and EOS ASTER image in 2003 is difficult to use for the change mapping. The Landsat MSS of 1977, Landsat TM of 1990 and 1996, and Landsat ETM+ of 2000 show the glacier change results (Table 6.2).

The result clearly shows that the glaciers were retreated from 1977 to 2000. The change of area and length of the five glaciers is shown in the Table 6.2. All the five glaciers area as well as length had shrunk. Among the five glaciers, maximum area shrunk is of the 5O191D0015 Glacier and minimum of 5O191D0002 Glacier. Maximum length (0.75 km) of 5O191D0024 Glacier and minimum length (0.21 km) of 5O191D0011 Glacier had reduced in last 24 years. In this region the average retreat of glaciers area is 0.028 km^2 and length of Valley Glaciers reduced by 20 m per year.

Table 6.2 The change values of five glaciers on the northern slope of the Laptshegang Mountain

		DATE(yyyy-mm-dd)				
Glacier ID	**ITEMS**	**1977-01-01**	**1990-12-21**	**1996-10-18**	**2000-11-22**	**Diff. in 1977-2000**
5O191D0002	Area(km^2)	6.97	6.48	6.47	6.46	0.51
	Length(km)	7.88	7.71	7.54	7.48	0.40
5O191D0011	Area(km^2)	10.66	10.47	10.06	10.03	0.63
	Length(km)	5.18	4.96	4.89	4.83	0.21
5O191D0015	Area(km^2)	6.81	5.79	5.76	5.73	1.08
	Length(km)	3.28	2.87	2.83	2.71	0.57
5O191D0021	Area(km^2)	4.92	4.60	4.42	4.41	0.51
	Length(km)	3.08	2.79	2.59	2.56	0.52
5O191D0024	Area(km^2)	2.60	2.02	2.00	2.00	0.60
	Length(km)	1.70	0.95	0.95	0.95	0.75

7 MONITORING OF GLACIAL LAKES

According to the two period's inventories of glacial lakes, the glacial lakes with significant change were analysed in detail, by using the Landsat MSS, Landsat TM, Landsat ETM+, and EOS ASTER data of 1977, 1984, 1990, 1996, 2001 and 2003 respectively. For the analysis two lakes from the southeastern slope of the Xixiabangma Mountain and four lakes from the northern slope of the Laptshegang Mountain are taken as case study from the Poiqu River basin.

7.1 LAKES ON THE SOUTHEAST SLOPE OF XIXIABANGMA MOUNTAIN

The GangxiCo Lake (No. 5O191C0011) and LumuChimi Lake (No. 5O191B0030) are two large glacial lakes in Poiqu basin. Both of these lakes posed danger and remarkable change in size from 1977 to 2003. These lakes have been investigated during 1987 by LIGG/WECS/NEA field investigation (LIGG/WECS/NEA, 1988).

GANGXICO LAKE (Lake No. 5O191C0011)

This lake is at approximately 5300 m a.s.l., north of the Congduipu Gully and flowing into the Poiqu River in a general east direction. The lake is completely surrounded by moraines which exhibit very steep and loose lake-side slopes; its feeder is a long glacier from the slopes of Mt. Xixiabangma (Figure 7.1).

The steep eroding moraine slopes on the lake side may be a result of a large range of water level fluctuations and/or due to wave action generated by ice calving of the glacier tongue in contact with the water. With the help of different satellite images of different date the lake area delineated for the analysis of the lake activity. The growth of the lake is shown in the Table 7.1 and Figure 7.3. The lake area in 1977 was 2.05 sq km and expanded to 3.84 sq km in 2003 in the form of largest lake in the Poiqu River basin.

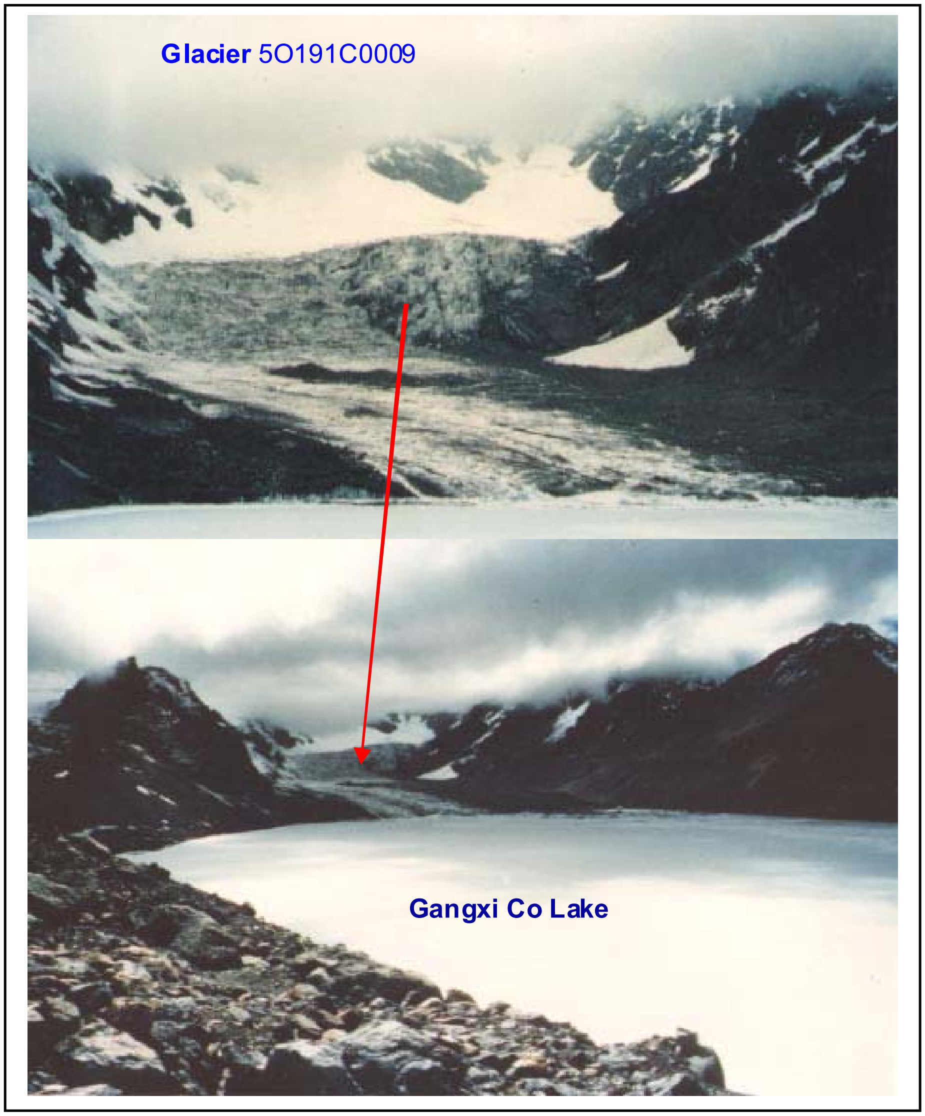


Figure 7.1:GangxiCo Lake at the tongue of Glacier 50191C0009 in 1987

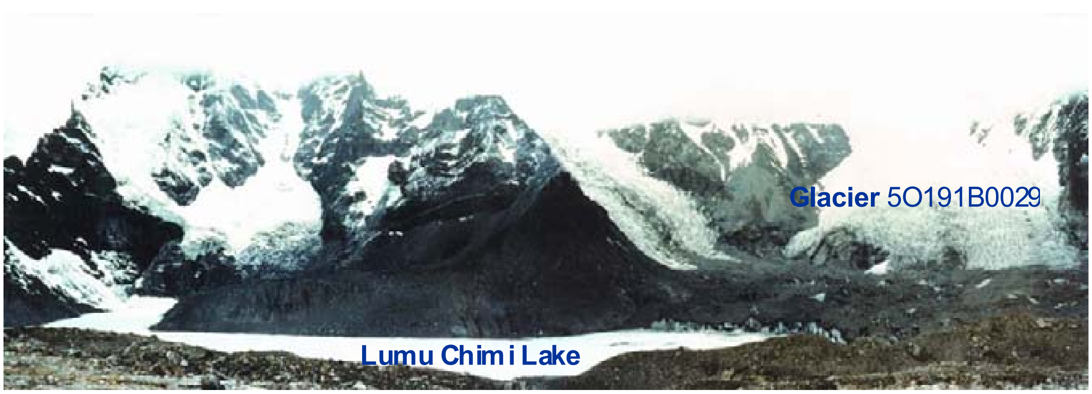


Figure 7.2: LumuChimi Lake at the tongue of Glacier 50191B0029 in 1987

LUMUCHIMI LAKE (Lake No. 5O191B0030)
LumuChimi Lake lies approximately at 5030 m a.s.l. in the headwaters of the Jiapu Gully, the northern tributary of Congduipu Gully. This is the second largest end moraine dammed lake in the Poiqu Basin with an area of 1.67 sq km in 1977 and 3.64 sq km in 2003.

There is a complex valley glacier developed behind this lake. This glacier originated from the southeastern side of Mt. Xixiabangma and consists mainly of two ice-flows (Figure 7.2). From the headwaters to the glacial tongue area the ice surface has a steep slope, forming two ice falls, where ice layers are broken. The glacial tongue, formed by two ice-flows is rather gentle with morainic material covering its surface. The glacial terminus connects to the glacier lake through an ice cliff. The vertical altitude difference between the source and its terminus of 5O191B0029 glacier (Glacier No.35 of LIGG/NEA/WECS inventory of 1987) is 2900m. The glacier is mainly nourished by snow-fall, snow-avalanche and snow-drift.

Similar to the glacier change analysis, the linear regress model was used to explain the average change in past every year from 1977 to 2003 (Figure 7.4). For the lake LumuChimi Lake, there are around 0.076 km^2 of area increased every year, as well about 0.069 km^2 for the GangxiCo Lake.

Table 7.1 Area change from 1977 to 2003 of GangxiCo Lake (No. 5O191C0011) and the LumuChimi Lake (No.5O191B0030)

LAKE-ID	AREA (sq.km.)					
	In 1977	In 1984	In 1990	In 1996	In 2000	In 2003
GangxiCo	2.05	2.18	2.91	3.26	3.63	3.84
LumuChimi	1.67	1.97	2.37	2.98	3.41	3.64

7.2 THE GLACIAL LAKES ON THE NORTH SLOPE OF LAPTSHEGANG MOUNTAIN

The glacial lake received more melt from the retreating glacier, which can lead to three kinds of phenomenon. First, when the lake cut the glacier tongue or debris at the ground surface, the glacial lake area will visibly increase. Secondly, when the lake eroded the debris at its base, the depth of glacial lake will increase, instead of the area. The third one is that the lake level rises without the eroding or cutting. Regarding the limit of visible remote sensing images, the depth cannot be monitored by remote sensing images such as the Landsat MSS, TM, ETM, and EOS ASTER images. Therefore, the first phenomenon (lake area change) will be analyzed and discussed here for the glacial lake change.

Four glacial lakes with the area change are shown in the Table 7.2. Due to presence of some seasonal snow cover, the Landsat MSS image in 1984 and EOS ASTER image in

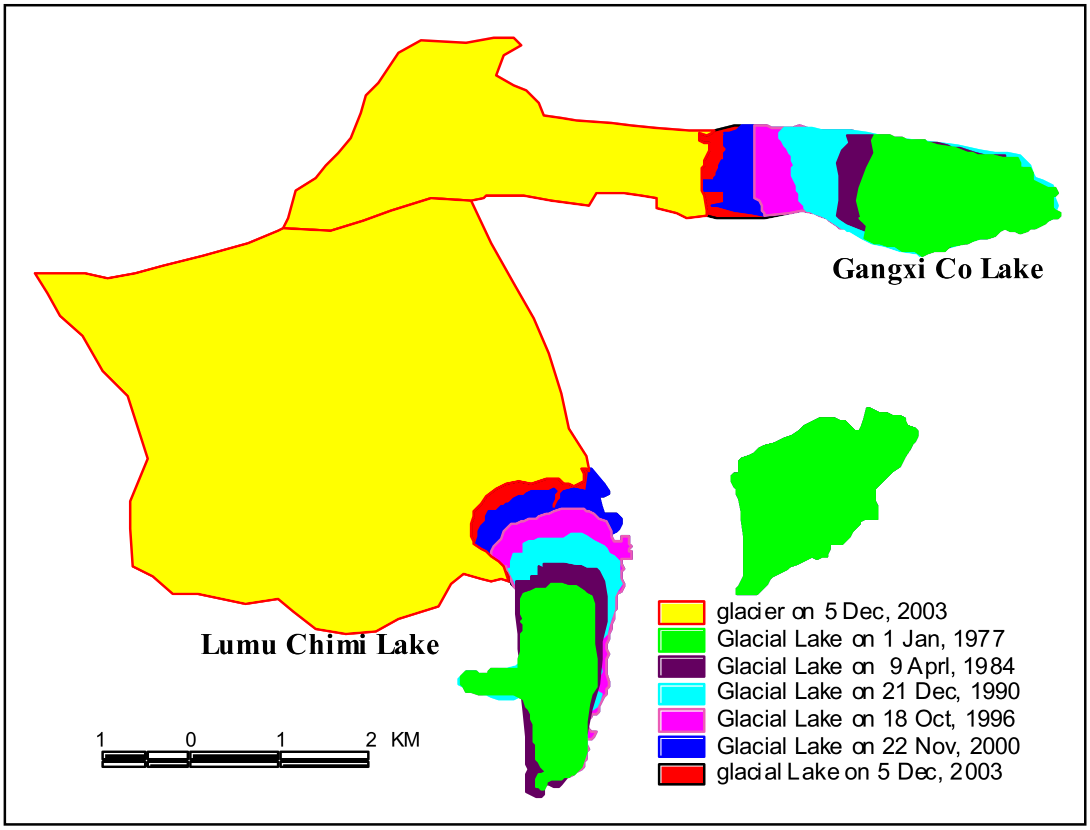


Figure 7.3 Change map of Gangxi Co Lake (upper) and the LumuChimi Lake (below)

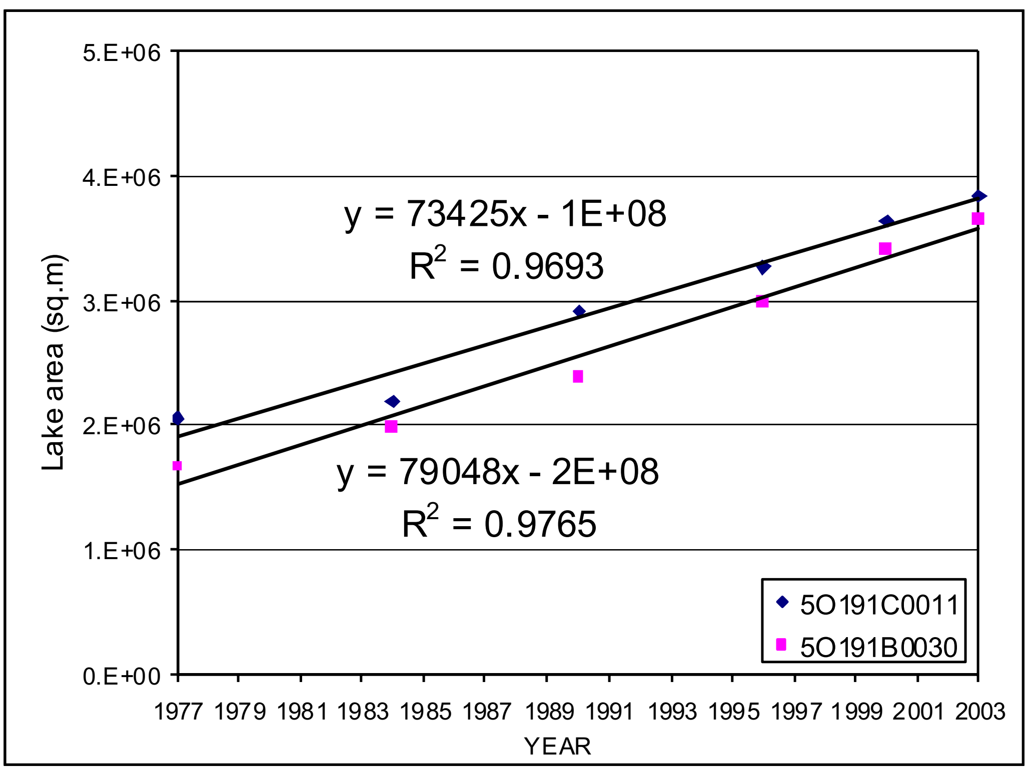


Figure 7.4 The change of lake area and the trend analysis

2003 can not be used for the change mapping (Figure 7.4). The subsets from satellite images are illustrated in Figure 7.5 and the Table 7.2 gives the detail data.

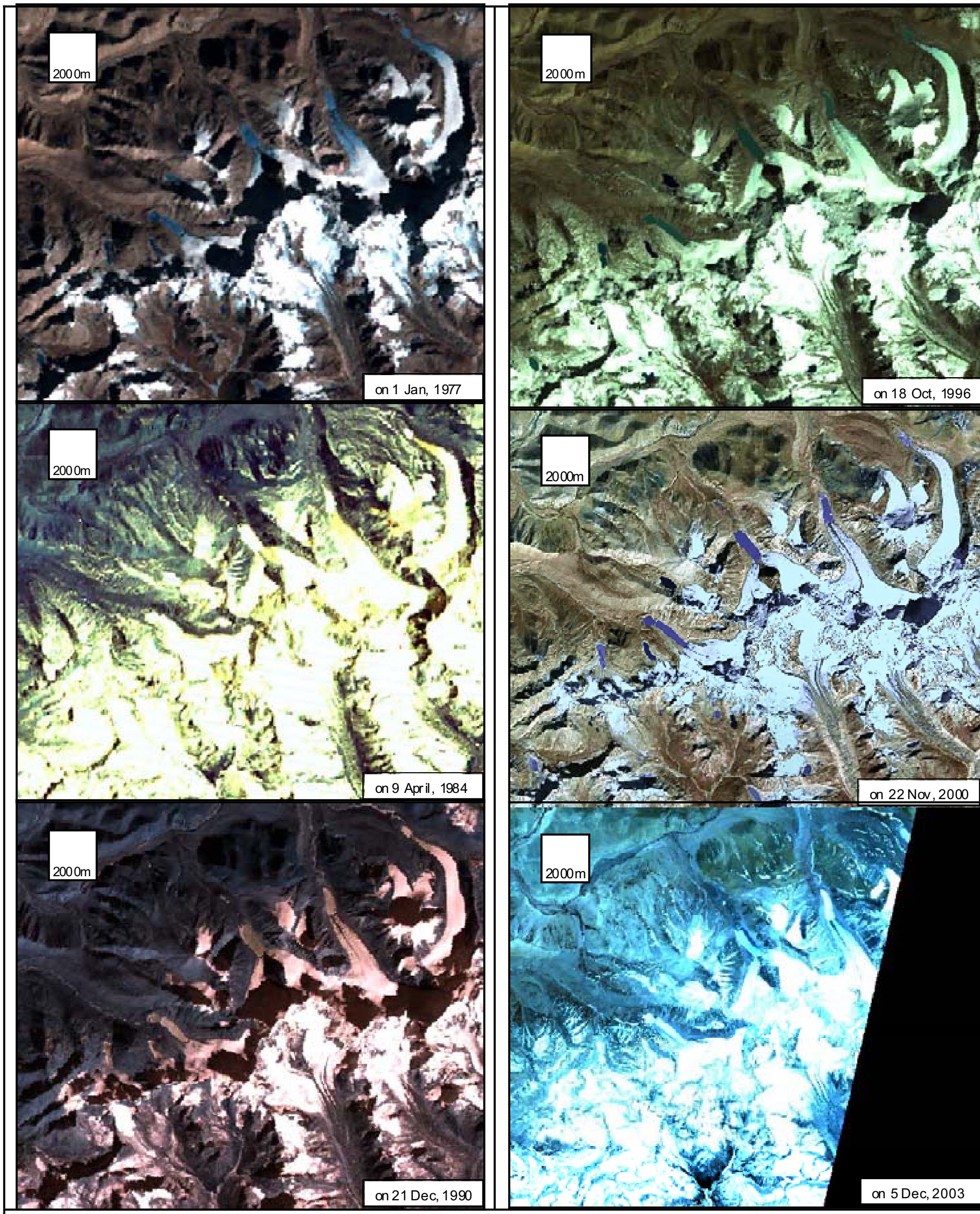


Figure 7.5 The multi-temporal remote sensing satellite images around the northern slope of Laptshegang Mountain

Table 7.2 The area of four glacial lakes on the northern slope of the Laptshegang Mountain from 1977 to 2000					
Glacial lake ID	DATE(yyyy-mm-dd)				
	1977-01-01	1990-12-21	1996-10-18	2000-11-22	Growth/yr
	Area in sq km				
5O191D0001	0.08	0.16	0.16	0.19	0.005
5O191D0002	0.28	0.37	0.39	0.43	0.006
5O191D0007	0.49	0.59	0.61	0.619	0.005
5O191D0009	0.51	0.54	0.58	0.62	0.005

In average the Lakes 5O191D0002, 5O191D0007 and 5O191D0009 have grown by 1.25 times and the Lake 5O191D0001 has grown by 2.5 times in 24 years (from 1977 to 2000). As the glaciers are retreated as the impact the lakes area are increased. All the four lakes had grown their size from 0.11 to 0.15 sq km since 1977 to 2000 with the average growth of around 0.005 sq km in the Laptshegang Mountain area.

8 CONCLUSIONS

In Poiqu basin, runoff is in increasing trend from 1990s, the temperature is growing up, and snowmelt is increasing. The basins with a lot of glaciers and glacial lakes needed real-time monitoring and Early Warning Systems (EWS) to minimize the GLOF hazard.

The Poiqu River basin comprises of 153 glaciers with an area of 243.86 sq. km in 1988 151 glaciers with an area of 231.58 sq. km in 2000. From 1988 to 2000 the loss of glaciers in the Poiqu River basin is 12.28 km^2 in area which is around five percent of the total area.

The Valley glaciers with IDs 5O191B0029 and 5O191C0009 on the eastern slope of the Xixiabangma retreated 0.05 km^2 and 0.06 km^2 area and 45 m and 68 m in length respectively per year since 1977. Similarly the analysis on the five Valley Glaciers on the northern slope of the Laptshegang Mountain had also shown the glacier shrunk. In this region the average retreat of glaciers area is 0.03 km^2 and length of Valley Glaciers reduced by 20 m per year.

The Poiqu basin consists of 119 lakes with an area of 13.42 km^2 in 1980s and 139 lakes with an area of 16.39 km^2 in 2000s. The lakes Gangxi Co and LumuChimi on the eastern slope of the Xixiabangma had grown 1.87 and 2.18 times respectively. The lake area on the northern slope of the Laptshegang Mountain is comparatively smaller in size but the growth rate is from 1.2 to 2.5 times.

Altogether 9 glacial lakes are identified as potentially dangerous and recommended for detail field investigation. To minimize GLOF hazard before mitigation, ten sites have been proposed for setting up the Early Warning Systems.

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