Pumqu (Arun), Rongxer (Tama Koshi), Poiqu (Bhote-Sun Koshi), Jilongcangbu (Trishuli), Zangbuqin (Budhigandaki), Majiacangbu (Humla Karnali), Daoliqu and Jiazhagangge Basins

Tibet Autonomous Region, People's Republic of China

Inventory of Glaciers and Glacial Lakes and
the Identification of Potential Glacial Lake Outburst Floods (GLOFs)
Affected by Global Warming in the Mountains of Himalayan Region

Cold and Arid Regions Environmental and Engineering Research Institute
Bureau of Hydrology Tibet, Tibet Autonomous Region of P. R. China
Asia-Pacific Network for Global Change Research
global change SysTem for Analysis, Research and Training
International Centre for Integrated Mountain Development
United Nations Environment Programme/Regional Resource Centre for Asia and the Pacific

Pumqu, Rongxer, Poiqu, Zangbuqin, Jilongcangbu, Majiacangbu, Daoliqu and Jiazhagangge basins

Tibet Autonomous Region, People's Republic of China

Inventory of Glaciers, Glacial Lakes and the Identification of Potential Glacial Lake Outburst Floods (GLOFs) Affected by Global Warning in the Mountains of Himalayan Region

Wu Lizong, Che Tao, Jin Rui & Li Xin (CAREERI)

Gong Tongliang & Xie Yuhong (BHT)

Pradeep Mool, Samjwal Bajracharya, Basanta Shrestha & Sharad Joshi (ICIMOD)

Cold and Arid Region Environmental and Engineering Research Institute

Bureau of Hydrology Tibet

International Centre for Integrated Mountain Development

Asia-Pacific Network for Global Change Research

global change SysTem for Analysis, Research and Training

United Nations Environment Programme/Regional Resource Centre for Asia and the Pacific

2005

Foreword

The glaciers of the Hindu Kush-Himalayas (HKH) are nature's renewable storehouse of fresh water on the top of their watershed from which hundreds of millions of people downstream benefit just when it is most needed in the dry hot season before the monsoons. These high frozen reservoirs release water serve as a perennial source for the tributaries of the Ganges River that wind their way through thousands of square kilometres of grazing, agricultural, and forest lands and are used for irrigation, drinking water, energy, and industrial purposes.

However, these glaciers are retreating in the face of accelerating global warming. They are particularly vulnerable to climate change, and the resultant long-term loss of natural fresh water storage will have as yet uncalculated effects on the communities downstream. More immediately, as glaciers are retreating, some glacial lakes are formed behind the new exposed terminal moraines. Rapid accumulation of water in those lakes, particularly in those adjacent to receding glaciers, can lead to a sudden breaching of the unstable 'dam' behind which they have been formed. The resultant discharge of huge amounts of water and debris can cause a **glacial lake outburst flood (GLOF),** and often have catastrophic effects downstream.

Many glacial lakes are known to have formed in the HKH region in the last half century and a number of GLOFs have been reported in the region during the last few decades. These GLOF events had resulted in many deaths, as well as the destruction of houses, bridges, fields, forests, and roads. The lakes at risk, however, are situated in remote and inaccessible areas. When they burst, the local communities may have been devastated, while those far away downstream were largely unaware of the event.

In 1964, the Gelhaipuco GLOF occurred along the Pumqu valley in Tibet Autonomous region (Tibet Autonomous Region) of Peoples' Republic of China. Severe damage and heavy economic losses occurred in the Chinese territory and downstream in the Arun valley in Nepal. GLOF from the Ayaco Lake experienced each year from 1968 to 1970. In recent years, there have been many reports about GLOF events that have led to the wreck of highways.

Despite numerous studies of individual cases, there is still no detailed inventory of glaciers, glacial lakes, GLOF events or potential GLOF sites in the HKH region – let alone of their impact on downstream populations and investments.

The International Centre for Integrated Mountain Development (ICIMOD) through its Mountain Environment and Natural Resources' Information Systems (MENRIS) Division in partnership with the United Nations Environment Programme's Regional Resource Centre for Asia and the Pacific (UNEP/RRC-AP) conducted a study entitled "Inventory of glaciers, glacial lakes and glacial lake outburst floods and monitoring and early warning systems in Nepal and Bhutan" from June 1999 to March 2002. The project prepared spatial database on the glaciers and glacial lakes of Nepal and Bhutan with the application of remote sensing (RS) and geographic information systems (GIS). The main purpose of the study was to assess the threat from glacial lakes and to highlight those where GLOF events are likely to occur and cause serious damage to human life and property. This comprehensive report and digital database will be useful to scientists, planners, and decision-makers in many areas. Through their informed actions, we hope it will contribute to improving the lives of those living in the mountains, and help safeguard future investments for the benefit of many people in the region.

Comparable information from other part of the Hindu Kush – Himalayan (HKH) region is not present in the required level of details. In continuation of ICIMOD's programme on glaciers and glacial lakes study, studies in other parts of HKH region with co-funding from APN and START and in collaboration with the national institutions/organizations started from March 2002 in some selected basins of India, China and Pakistan. In 2002-2003 Tista Basin in Sikkim Himalaya of India, Pumqu basin in Tibet Autonomous Region of Peoples' Republic of China and Astor sub-basin in Indus basin of Pakistan were studied. In 2003-2004 Himachal Pradesh Himalaya of India, Poiqu and Rongxer basins in Tibet Autonomous Region of Peoples' Republic of China, and five sub-basins (Upper Indus, Jhelum, Shingo, Shyok and Shigar) in Indus basin of Pakistan were studied. In continuation of this Jilongcangbu, Zangbuqin, Majiacangbu, Daoliqu and Jiazhangangge basins of Tibet Autonomous Region of Peoples' Republic of China; Uttaranchal Himalaya of India; Gilgit, Chitral, Hunza and Swat River basins of Indus Basin in Pakistan were studied in 2004-2005.

One of the major objectives of the study was to identify areas where GLOF events had occurred and lakes that could pose a potential threat of GLOF in the near future. Out of a surprisingly large total of 824 glacial lakes, the researchers found 77 lakes that are potentially dangerous recommend for further study in the Pumqu, Rongxer, Poiqu, Zangbuqin, Jilongcangbu, Majiacangbu, Daoliqu and Jiazhagangge basins of Tibet Autonomous Region of Peoples' Republic of China. These results thus provide the basis for the development of a monitoring and early warning system and for the planning and prioritization of disaster mitigation efforts that could save many lives and properties situated downstream as well as guide line for infrastructure planning. In addition, it is anticipated that this study will provide useful information for many of those concerned with water resources and land-use planning.

This document also includes a description of the methods used to identify glaciers, glacial lakes, and glacial lakes that may pose a threat along with an inventory (and maps) of the glaciers and glacial. A summary of the results of the studies of various glaciers, glacial lakes and a brief review of the causes and effects of known GLOF has also been provided. This publication, along with other sister publications on the glaciers and glacial lakes are designed to begin filling this pressing need. Taken together, the database will greatly enhance the ability of global and regional climate researchers, national policy makers and water resource planners, as well as the general public, to understand and mitigate GLOF-associated hazards, thus linking science to policy.

This project has enabled further strengthening of the collaboration between APN, SRART, ICIMOD, CAREERI, BHT UNEP, and GLIMS to continue to assist in developing regional capacities and co-operation.

J. G. Campbell (Ph.D.)	Prof. Shi Yangfeng
ICIMOD	CAREERI

Acknowledgements

We highly acknowledge Dr. Mi Desheng, associate Prof. Wang Jianhua and Mr. Ran Youhua of CAREERI for their invaluable help and suggestion in interpreting the remote sensing images. We are also grateful to Mrs. Wei Hong of CAREERI for digitizing the topographic maps and remote sensing image analysis. In 1980s, Prof. Liu Chaohai et al. edited the book with a name of "Report on first expedition to glaciers and glacier lakes in the Pumqu and Poiqu River basins, Xizang, China", and their results are very useful to the research at present. In 2002, Mr. Mi Desheng and Prof. Xie Zichu edited the Glacier Inventory of China, in Ganga Drainage Basin and Indus River Drainage Basin, which provided the basic attribution information of glaciers. Other CAREERI staff members who have assisted in the study include Mr. Tang Han, Mrs. Jin Dehong, Mr. Xu Tao. We would like to thank them all for their contributions. We would like to thank Dr. Jeffrey S. Kargel, GLIMS, USGS, Mr. Bruce Raup at the National Snow and Ice Data Center, and Dr. Rick Wessels in USGS for providing ASTER images, which are the basic references of this study.

We would like to thank Dr. J. Gabriel Campbell, Director General of ICIMOD for overall coordination, supervision and timely supports during the implementation of the project. Other ICIMOD staff members who have assisted in the study include Ms. Monica Moktan, Ms. Mandakini Bhatta, Mr. Lokap Rajbhandari, Mr. Sushil Pradhan, Mr. Birendra Bajracharya, Mr. Sushil Pandey, Mr. Saisab Pradhan, Mr. Rajan Bajracharya and, Mr. Govinda Joshi. We would like to thank them all for their contributions

We would like to express appreciation and sincere thanks to Mr. Surendra Shrestha, Regional Director and Representative for Asia and the Pacific - UNEP and Director of UNEP/RRC-AP, Mr. Mylvakanam Iyngararasan, Ms. May Ann Mamicpic and Ms. Kitiya Gajesani of UNEP/RRC-AP for their strong support and advise.

Thanks are due to Mr. Sombo T. Yamamura, Director, Mr. Yukihiro Imanari, Executive Manager, Ms. Jody Chambers, Programme Manager, Mr. Martin Rice, Former Programme Manager, Communications and Development, Dr. Linda Anne Stevenson, Programme Manager, Ms. Sirijit Sangunurai, Programme Fellow, Mr. Tomoya Motoda, Technical Assistant, Mr. Toshiaki Mitani, Administrative Manager, Ms. Kanako Taguchi, Administrative Assistant, of Asia-Pacific Network for Global Change Research (APN) for their continuous support in the implementation of the project.

Last but not least we would like to express our sincere thanks to Prof. Roland Fuchs, Director, Dr. Hassan Virji, Deputy Director, Ms. Kathleen Landauer, Programme Associate Ms. Alix Cotumaccio, Programme Associate and Dr. Yna Calimon, former Programme Associate of International global change SysTem for Analysis, Research, and Training (START) Secretariat for their timely and strong support and advice while implementing the project.

Development Team
Wu Lizong, Che Tao, Jin Rui and Li Xin
Gong Tongliang and Xie Yuhong
Pradeep Mool, Samjwal Bajracharya, Basanta Shrestha, Sharad Joshi,
Kiran Shakya and Gauri Dangol

Acronyms

AP	Asia and the Pacific
APN	Asia-Pacific Network for Global Change Research
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
BHT	Bureau of Hydrology Tibet
CAS	Chinese Academy of Science
CAREERI	Cold and Arid Regions Environmental and Engineering Research Institute
CBERS	Chinese Brazilian Earth Resources Satellite
CBS	Central Bureau of Statistics
CCD	Charge Coupled Device Camera
CD	compact disk
DCS	Data collection system
DEM	digital elevation model
DHM	Department of Hydrology and Meteorology
DTS	Data Transmission System
EMS	electromagnetic spectrum
ENVI	Environment for Visualizing Images
EOS	Earth Observation System
ESCAP	Economic and Social Commission for Asia and the Pacific
ETM+	Enhance Thematic Mapper
ETH	Swiss Federal Institute of Technology
FCC	false colour composite
GCP	Ground control points
GIS	geographic information system
GLIMS	Global Land Ice Measurements from Space
GLOF	glacial lake outburst flood
HDDR	High Density Digital Recorder
HDF-EOS	Hierarchical Data Format for EOS HDF-EOS software
ICIMOD	International Centre for Integrated Mountain Development
IKM	Information and Knowledge Management
IRMSS	Infrared Multi-spectral Scanner
IRS1C	Indian Remote Sensing Satellite series 1C
IRS1D	Indian Remote Sensing Satellite series 1D
ITC	International Institute for Geo-Information Science and Earth Observation

JERS	Japanese Earth Resources Satellite
JICA	Japan International Cooperation Agency
Landsat	Land Resources Satellite
LIGG	Lanzhou Institute of Glaciology and Geocryology
LISS	Linear Imaging and Self Scanning Sensor (IRS)
masl	metres above sea level
MSS	Multi Spectral Scanner (Landsat)
NASA	National Aeronautics and Space Administration
NEA	Nepal Electricity Authority
NIR	Near infrared
PAN	Panchromatic Mode Sensor System (SPOT)
PCI	PCI Geomatics
RGB	red green blue
RMS	root mean square
RRC	Regional Resource Centre
RS	remote sensing
SEM	Space Environment Monitor
SPOT	Système Probatoire d'Observation de la Terre / Satellite Pour l'Observation de la Terre
SWIR	Short Wave Infra Red (JERS)
START	global Change SysTem for Analysis, Research and Training
TAR	Tibet Autonomous Region of Peoples Republics of China
TIR	Thermal infrared
TIN	Triangular Irregular Network
TM	Thematic Mapper (Landsat)
TTS	Temporary Technical Secretary
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
VNIR	Visible and Near Infra Red instrument
WECS	Water and Energy Commission Secretariat
WGI	World Glacier Inventory
WGMS	World Glacier Monitoring Service
WFI	Wide Field Imager
XS	Multispectral Mode Sensor System (SPOT)

Contents

Chapter 1

Introduction

The Tibet Autonomous Region of the Peoples' Republic of China is a mountainous region, occupied mostly by mountains and hills. The accumulation of water flows mainly from the mountain cause intensive erosion and drastic destruction. The floods always occur in the valleys of the mountainous region. Based on its source, floods can be divided into three types: plateau-rainstorm mountain flood, melted-snow mountain flood, and melted-glacier mountain flood. The glaciers, some of which consist of huge amounts of perpetual snow and ice, are found to create many glacial lakes. These glaciers as well as glacial lakes are the sources of the headwaters of many great rivers in the region. Most of these lakes are located in the down valleys close to the glaciers. They are formed by the accumulation of vast amounts of water from the melting of snow and ice cover and by blockage of end moraines. The sudden break of a moraine may generate the discharge of large volumes of water and debris causing floods.

Since the second half of the 20th century, several glacial lakes have developed in the Hindu Kush-Himalayan (HKH) region. This may be attributed to the effect of recent global warming. The glacial lakes are formed on the glacier terminus due to the recent retreating processes of glaciers. The majority of these glacial lakes are dammed by unstable moraines, which are formed by glaciations during the Little Ice Age.

Occasionally, a lake outbursts releasing 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 HKH countries of China (Tibet), Nepal, India, Pakistan, and Bhutan.

According to the World Glacier Inventory (WGI), China carried out glacier inventory throughout the country from 1979. This work was completed in 2002 and documented 21 books. This glacier inventory took into consideration with limited extent of glacial lakes, but did not undertake a systematic inventory. 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".

The change of glaciers in the Himalaya-China region, influenced by the global change of climate, is marked and distributed asymmetrically in different areas. A second inventory of glaciers and glacial lakes could statistically detect the change and analyze the activity of glaciers. The study of satellite images indicates the presence of glaciers and glacial lakes and occurrences of GLOFs in the Himalayas. The impact on downstream of GLOFs is reported to be highly destructive in nature and lead to long-term secondary environmental degradation in the valleys, both physically and socio-economically.

Cold and Arid Regions' Environmental and Engineering Research Institute of the Chinese Academy of Science and the Bureau of Hydrology Tibet of 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.

For mapping and compiling of the inventory of glaciers and glacial lakes, the methodology is used similar to Nepal and Bhutan (Mool et al. 2001a and Mool et al. 2001b), which is based on the research of the Temporary Technical Secretary (TTS) for the World Glacier Inventory (WGI) of the Swiss Federal Institute of Technology (ETH), Zurich (Muller *et al.* 1977 and the World Glacier Monitoring Service [WGMS] 1989).

1.2 OBJECTIVE

- To understand the GLOF phenomenon by creating an inventory of existing glacial lakes and monitoring the GLOF events on a regular basis
- To establish an effective early warning mechanism to monitor GLOF hazards using remote sensing (RS) and geographic information systems (GIS) in the Hindu Kush-Himalayan region
- To build the capabilities of national institutions to assess and monitor the GLOF phenomenon
- To disseminate the results and outputs among relevant organizations in the region that could make use of this information for GLOF hazard prevention and mitigation planning

1.3 OUTPUTS

- An inventory of glaciers and glacial lakes of Pumqu, Rongxer, Poiqu, Zangbuqin, Jilongcangbu, Majiacangbu, Daoliqu and Jiazhangangge basins
- Identification of potential risk lakes
- Recommendations for the establishment of a system for monitoring potential risk lakes using RS and GIS
- Strengthened capabilities of the national institutions to implement an early warning system for GLOF hazard monitoring
- Informed relevant institutions regarding the results and potential risks, thereby increasing the capability to plan for and prevent or mitigate the risks
- Dissemination of the results and outputs to relevant institutions

1.4 ACTIVITIES

- Glacier and glacial lake inventory

  - Acquisition of the Landsat-5 TM image of 1990 and Landsat-7 ETM+ images of 2000, both covering the research region
  - Collecting GIS data layers including Digital Elevation Models (DEM) with resolution 28.5m from GLOF project
  - Obtaining the spatial and attribute information of glaciers and glacial lakes
  - Data analysis and report writing

- Monitoring potential risk lakes

  - Acquisition of Landsat-5 TM image of 1990 and Landsat-7 ETM+ images of 2000, both covering the research region for glacial lakes
  -
  - Collection of inventory data of glaciers and glacial lakes from Report on First Expedition to Glaciers and Glacier Lakes in The Pumqu (Arun) and Poiqu (Bhote-Sun Koshi) River basins, Xizang (Tibet), China and Glacier Inventory of China -The Ganga Drainage basin, Indus River Drainage Basin.
  - Collection of Meteorological data like temperature, rainfall and evaporation
  - Field checking and validation of results
  - Report writing

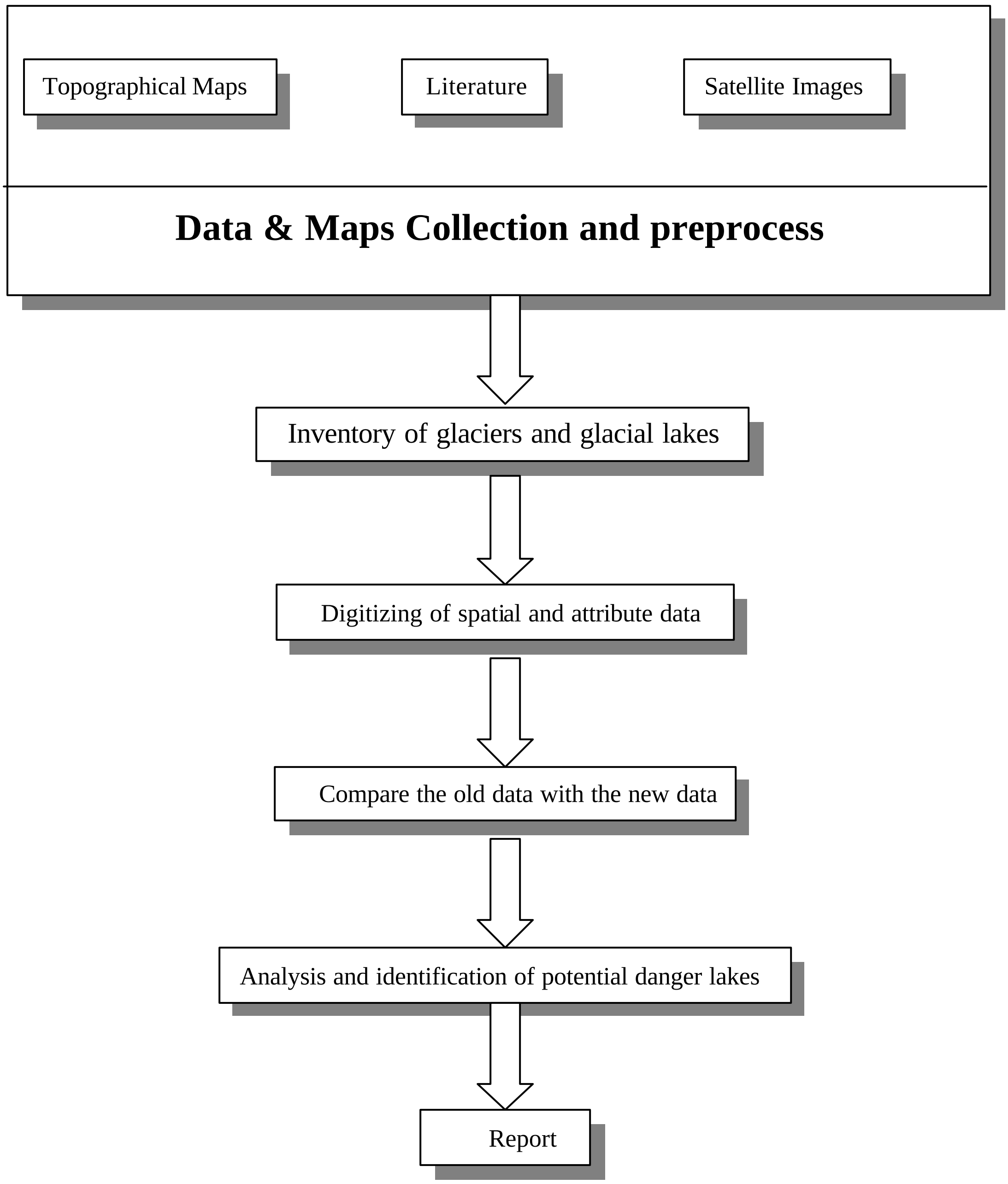
- Establishment of an early warning system

  - Developing the methodology using RS and GIS techniques for the inventory of glaciers and glacial lakes and for the GLOF monitoring and early warning system

- Results dissemination/publication

  - Publication of a comprehensive report including (1) to (3) above
  - Dissemination of results and outputs in the form of reports, on CD, and through the Internet
  - Organization of a workshop to release the results and outputs

1.5 FLOW CHART



Chapter 2

General Characteristics of the Himalaya-China Region

2.1 PHYSICAL FEATURES

The Himalaya-China region are situated on the south of the Tibetan Autonomous Region of the Peoples' Republic of China. The research regions include Pumqu, Rongxer, Poiqu, Zangbuqin, Jilongcangbu, Majiacangbu, Daoliqu and Jiazhangangge basins (see figure 2.1). The total area of the Himalaya-China research regions within China is 38325 km^2. The Himalaya -China regions have average altitude above 4500 m and receive abundant precipitation of monsoon form Indian Ocean, both of them providing favorable topography and climate condition to develop glaciers.

The Pumqu (Arun) River Basin is situated in the southwest of Tibet Autonomous Region of P. R. China and between 27°49?N to 29°05?N latitude and 85°38?E to 88°57?E longitude. It is bounded to the north by the Mimanjinzhu Range of the Gandiseshan border on the Yarlungzangbo (Brahmaputra) River, and to the south by the world's highest-Himalayan Range neighbouring Nepal and Sikkim. The basin extends into the Biakuco continental lake in the west. The Yap Mountains seated in the southwest of the basin separate the Pumqu (Arun) and Poiqu (Bhote-Sun Koshi) River Basins. The eastern part of the basin extends into Mts. Qumo, Xaya and Joding boarding on Nyangqu River, a tributary of the Yarlungzangbo (Brahmaputra) River. The total drainage area of the Pumqu (Arun) River Basin within Tibet is 25307 km^2.The length from east to west is about 320km and the width from south to north is about 120 km.

The total drainage area of the Poiqu basin (Bhote-Sun Koshi) and Rongxer basin (Tama Koshi) within Tibet, China, is 3430 sq. km. The length from east to west is about 84 km and the width from south to north is about 69 km.

Both Pumqu River and Poiqu River originates from the northern slope of Xixiapama mountain, flows through Nepal and into the Ganga through the Koshi.

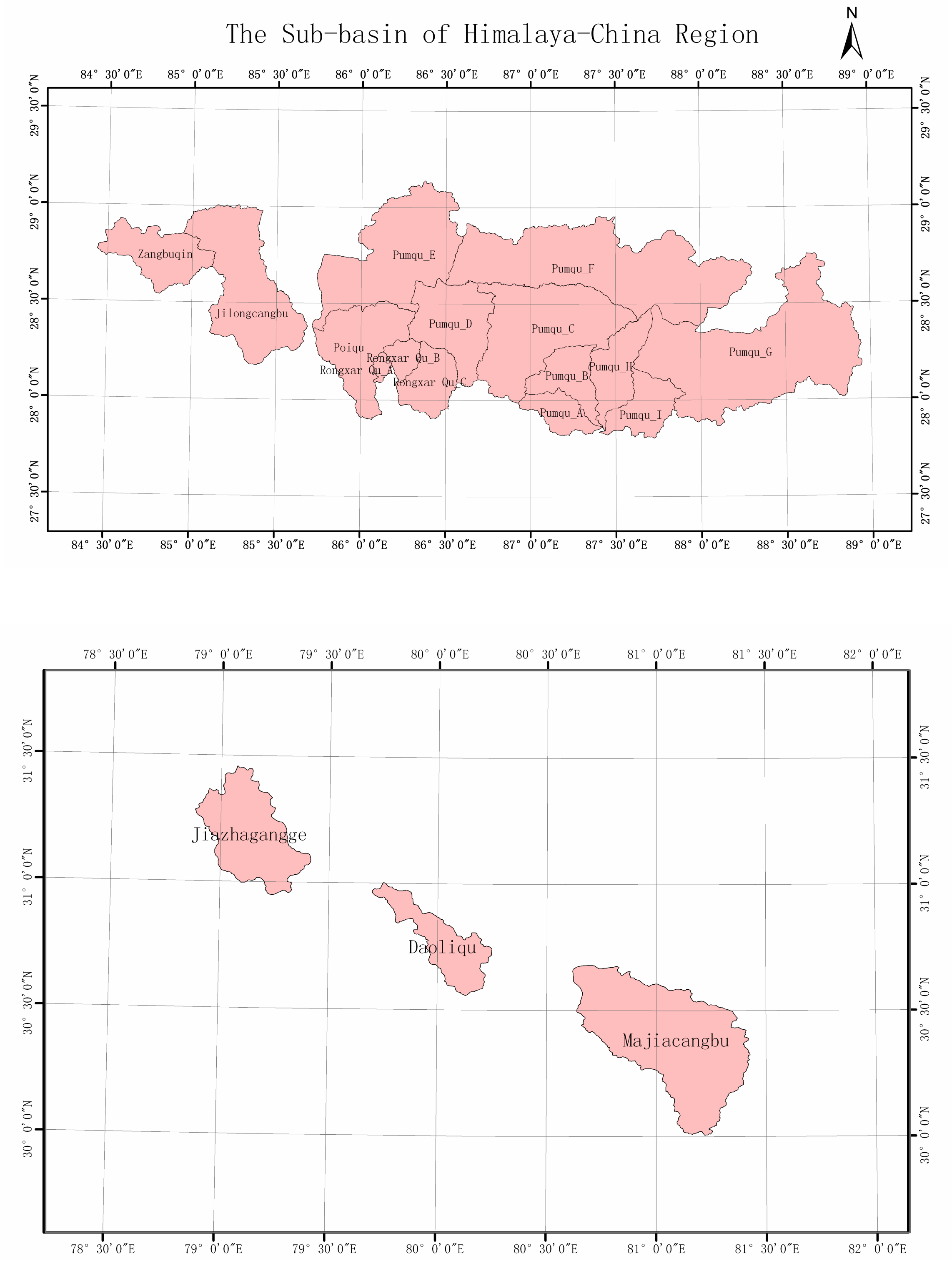


Fig 2.1 The sub-basins of Himalaya-China study regions

2.2 Climate

Being located on the leeward side of the Himalayan range of China receive considerably less precipitation than the southern Himalayan range. Generally, the precipitation in the Tibet basin decreases from west to east and also from south to north.

The major source of precipitation is the warm-moist air from the southwest monsoon. The precipitation decreases from south to north gradually. For example, 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 River is comparatively higher. In general, due to the barrier effect of the mountains, the annual mean precipitation decrease with the increase of altitude.

Meteorological data such as temperature, rainfall, and evaporation of the Himalaya-China region are available from the meteorological stations at Tingri from 1960 to 1987. The annual distribution of rainfall in the region is not uniform. About 96% of the annual precipitation occurs only in the summer season from June to September. There are two distinct wet and dry seasons in the basins, but in its southern part, the seasonal distribution of rainfall is reported to be even and the precipitation from June through September is approximately 50% of the annual precipitation.

The mean elevation of the Himalaya-China region is above 4,500 masl. Therefore, the annual mean air temperature is low because of the high altitude. 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.

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 in Chentang, the lower reaches of the Pumqu River basin near the Nepal/China boarder, is estimated at about 1,000mm.

2.3 RIVER SYSTEMS

The river systems in the Himalaya-China region are well developed (see Figure 2.2). The main tributaries of the Pumqu River are Rongpuqu, Yairuzangbo, Natangqu and Ganmazangbo. The left affluents of the Pumqu (Arun) River are Pamjuqu, Lopu, Loloqu, Yairuzangbo and Ganmazangbo are the right tributaries. Drainage areas and observed discharges of the main tributaries are presented in Table 2.1.

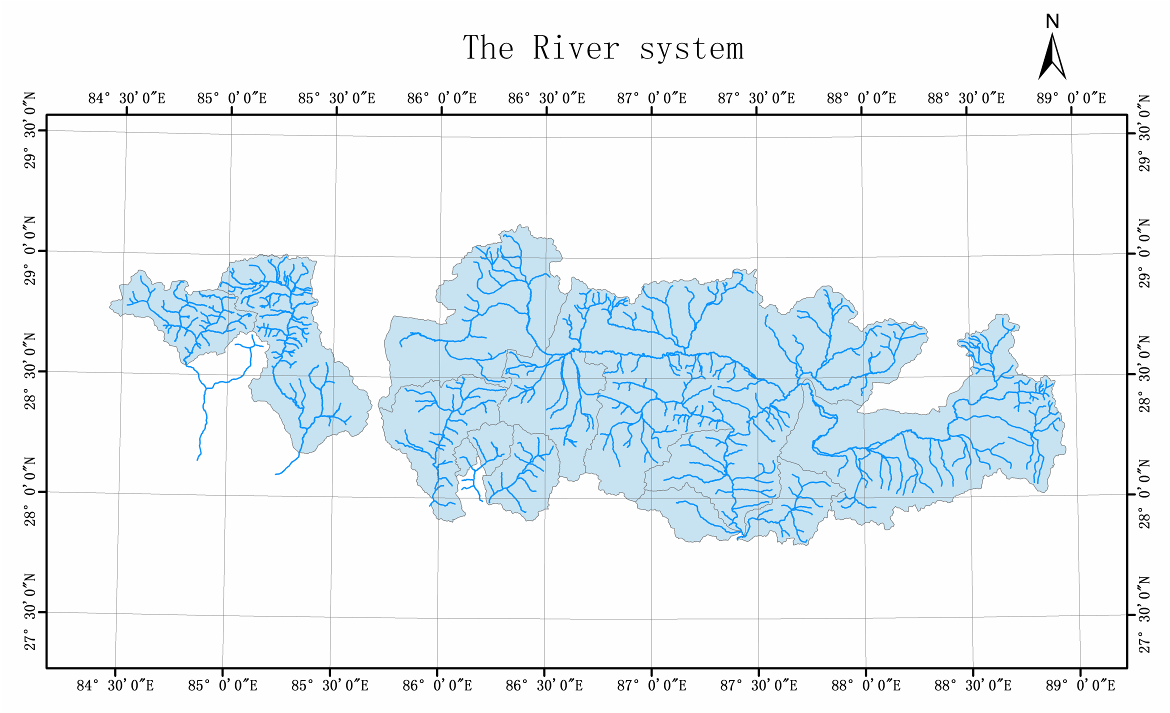
Table 2.1 The key elements of the main tributaries in the Pumqu (Arun) River basin

Name of Tributaries		Drainage		
		Length (km)	Area (km^2)	Ratio to total area within China (%)
Langlongqu	The right side	36	581	2.3
Jialaqu	The right side	38	563	2.2
Zongboxan	The right side	38	451	1.3
Raquzangbo	The right side	51	858	3.4
Rongpuqu	The right side	91	2360	9.3
Kadaqu	The right side	34	396	1.6
Ganmazangbo	The right side	50	665	2.6
Pamjuqu	The left side	41	1187	4.7
Lopu	The left side	34	480	1.9
Loloqu	The left side	53	2046	8.1
Yairuzangbo	The left side	198	8342	33.1
Natangqu	The left side	66	988	3.9
Pumqu	Mean steam	376	25307	100.0

The Poiqu basin in China quoted as 5O191 basin number and the downstream in Nepal is named Bhote-Sun Koshi. Rongxer basin in China quoted as 5O192 basin number and the downstream in Nepal is named as Tama Koshi. Both the basins are sub-basin of Koshi basin of Ganges basin.

The nine main affluents of Poiqu (Bhote-Sun Koshi) River are Lazapu, Tongpu, Gyaiyipu. Koryagpu, Targyailing, Karrup, Congduipu, Zhangzanbo and Pumqu. It is about 80 km in length and the total catchments area is 1987 km^2.

Rongxer River (Tama Koshi) originates from the Duoka Pula Mountain which elevation is about 5611m. There are so many glaciers at the source of the river. The total catchments area is 1484 km^2. The main river course is about 45 km in length.



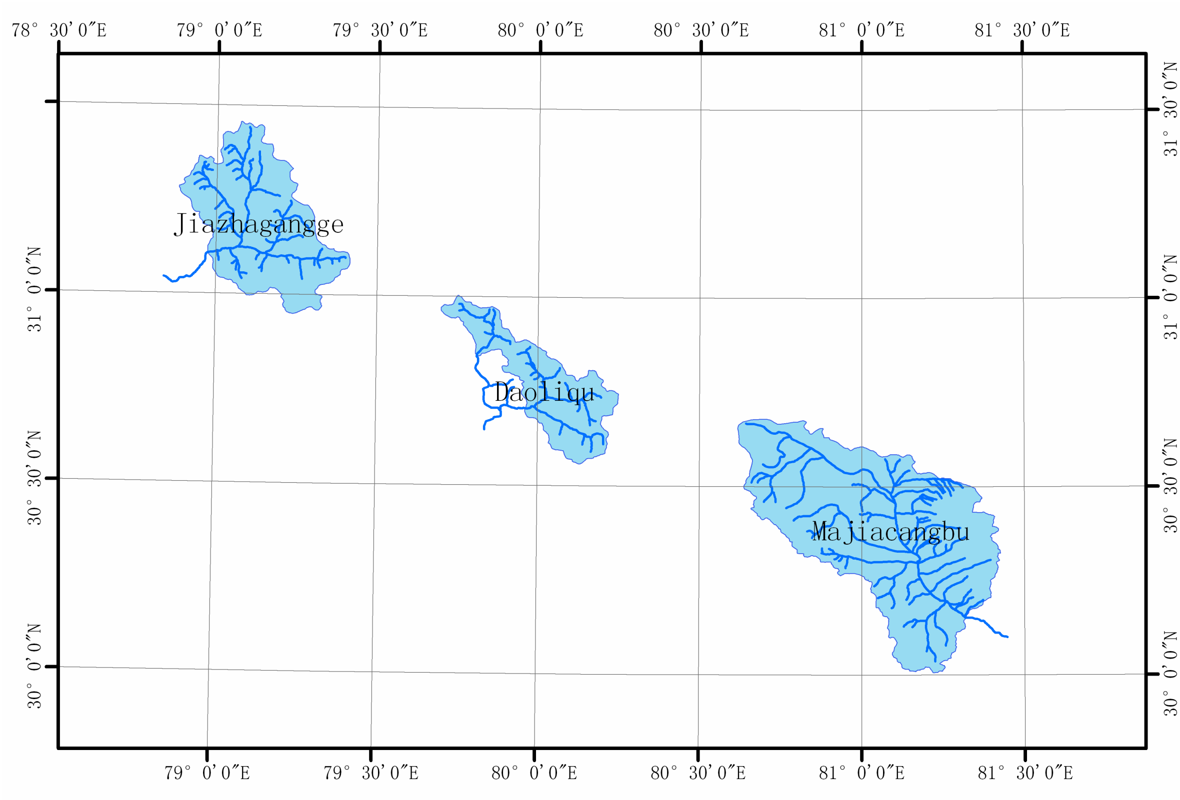


Figure 2.2 The River System in Himalaya-China Region

2.4 GEOLOGY AND GEOMORPHOLOGY

The Himalaya-China region is located in the middle of the Great Himalayan Range. The geological and geomorphological features have mainly depended on the upward motion of the Himalayas since the end of the Tertiary Period.

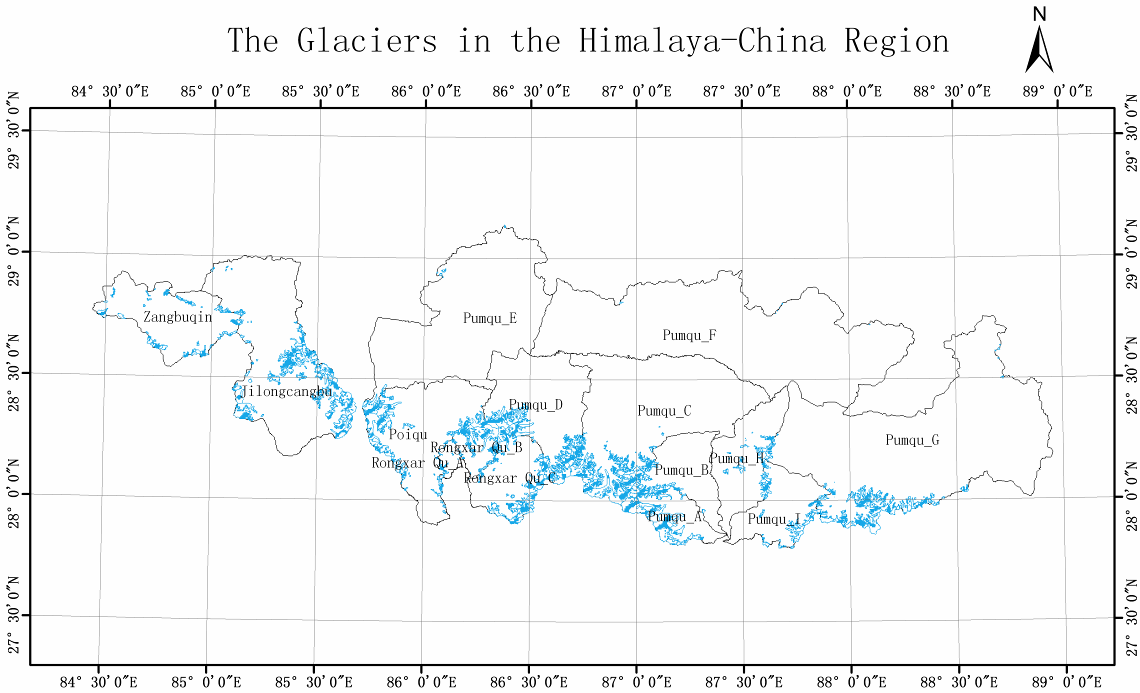
The basin lies in High Himalayan structural zone in-between the Central Fault Zone of the Himalayas and the Gyirongtogda-Dinggyenyela fault zone. This zone is the basement rock system of the northern edge ocean of the Indian Continent. It passes through the central reverse fault and covers the low Himalayan constructural zone southwards. The strata are mainly Nyalam Group of Pre-Sinian (Pre-Cambrian) System. The rocks are mostly kyanite-garnet-mica schist, kyanite-green landsite-biotite schist, mica-quartz schist etc. In the investigated region, there are complicated geological structures, evidence of intense earthquakes, older rock formations, and frequent neotectonic movements. These provide favorable geological conditions for the development of various landforms.

2.5 GLACIERS

A glacier is a huge flowing ice mass. The flow is an essential property in defining a glacier. Usually a glacier develops under conditions of low temperature caused by the cold climate, which in itself is not sufficient to create a glacier. There are regions in which the amount of the total deposited mass of snow exceeds the total mass of snow melt during a year in both the polar and high mountain regions. A stretch of such an area is defined as an accumulation area. Thus, snow layers are piled up year after year in the accumulation area because of the fact that the annual net mass balance is positive. As a result of the overburden pressure due to their own weight, compression occurs in the deeper snow layers. As a consequence, the density of the snow layers increases whereby snow finally changes to ice below a certain depth. At the critical density of approximately 0.83g cm^{-3}, snow becomes impermeable to air. The impermeable snow is called ice. Its density ranges from 0.83 to a pure ice density of 0.917g cm^{-3}. Snow has a density range from 0.01g cm^{-3} for fresh snow layers just after snowfall to ice at a density of 0.83g cm^{-3}. Perennial snow with high density is called firn. When the thickness of ice exceeds a certain critical depth, the ice mass starts to flow down along the slope by a plastic deformation and slides along the ground driven by its own weight. The lower the altitude, the warmer the climate. Below a critical altitude, the annual mass of deposited snow melts completely. Snow disappears during the hot season and may not accumulate year after year. Such an area in terms of negative annual mass balance is defined as an ablation area. A glacier is divided into two such areas, the accumulation area in the upper part of the glacier and the ablation area in the lower part. The boundary line between them is defined as the *equilibrium line* where the deposited snow mass is equal to the melting mass in a year. Ice mass in the accumulation area flows down into the ablation area and melts away. Such a dynamic mass circulation system is defined as a glacier.

A glacier sometimes changes in size and shape due to the influence of climatic change. A glacier advances when the climate changes to a cool summer and a heavy snowfall in winter and the monsoon season. As the glacier advances, it expands and the terminus shifts down to a lower altitude. On the contrary, a glacier retreats when the climate changes to a warm summer and less snowfall. As the glacier retreats, it shrinks and the terminus climbs up to a higher altitude. Thus, climatic change results in a glacier shifting to another equilibrium size and shape.

According to the glacier inventory of 1990, there are 1578 glaciers in the Pumqu, Rongxer, Poiqu, Zangbuqin, Jilongcangbu, Majiacangbu, Daoliqu and Jiazhangangge basins in China, with an area of 2906.017 km^2. The present study shows 1578 glaciers covering area of 2864.33 km^2.



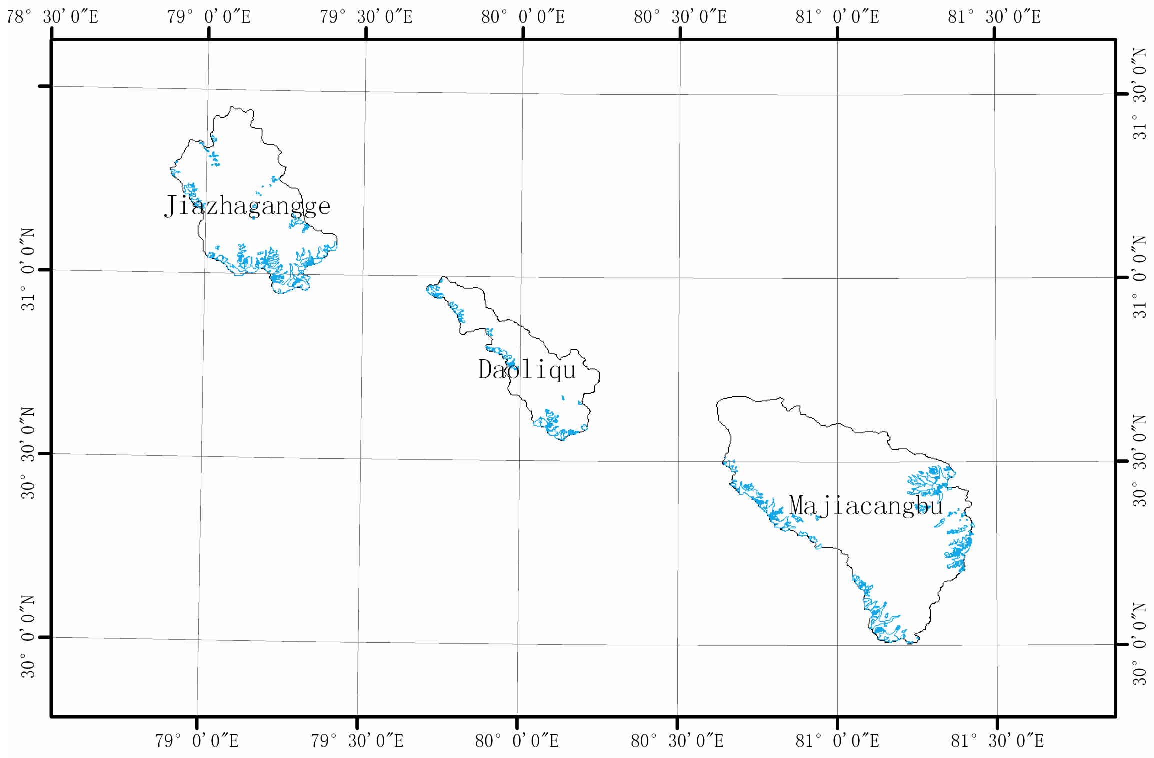
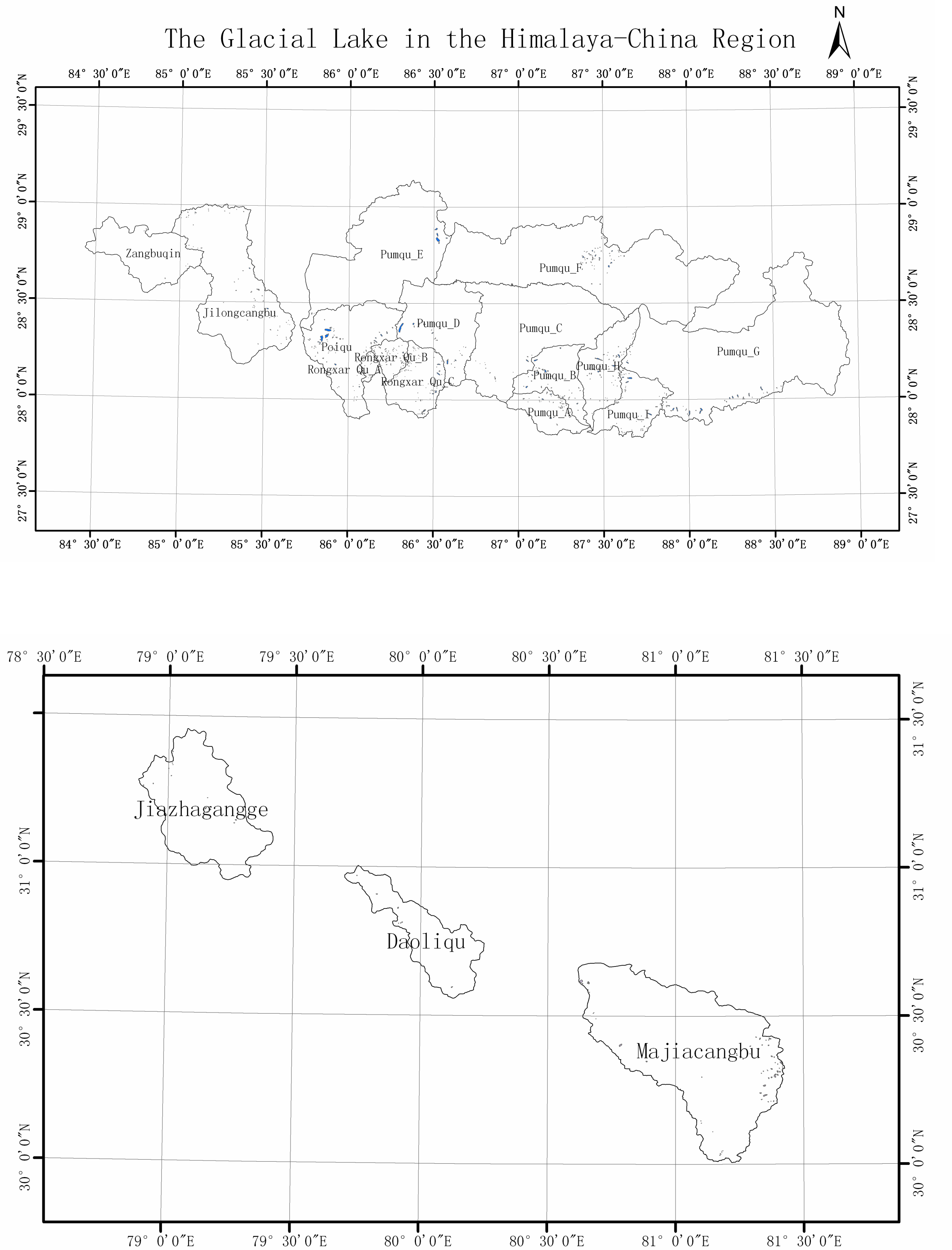


Figure 2.3 The Distribution of Glaciers in the Himalaya-China regions

2.6 GLACIAL LAKES

The study of glacial lakes is very important for the planning and implementation of any water resource development project. Past records show that glacial lakes have produced devastating floods and damage to major constructions and infrastructure. In 1987, a glacial lake inventory was made for the Poiqu and Pumqu River basin with large-scale topographical maps and aerial photographs.

According to the statistics of 1990s, there are 782 glacial lakes with an area of 74 km^2 in the Pumqu, Rongxer, Poiqu, Zangbuqin, Jilongcangbu, Majiacangbu, Daoliqu and Jiazhangangge basins in China. The present study shows 824 lakes with 85.2 km^2. According to contributing factors, the glacial lake can be divided into four types: cirque lakes, end moraine-dammed lakes, valley trough lakes, and blocked lakes. Of these, the most common are the end moraine-dammed lakes. Because the end moraine-dammed lakes mostly consist of end moraines formed in the Little Ice Age and close to their source glaciers, or connect directly with the glaciers, changes in the glaciers directly influence the water level of the glacier lake and the stability of the dam. At the same time, owing to the fact that the end moraine dams are composed of new and loose till, these are un-compacted and therefore unstable. This type of glacial lake burst easily and cause floods and debris flows.



The figure2.4 The Distribution of Glacial Lakes in Himalaya-China Region

2.7 GLACIAL LAKE OUTBURST FLOOD EVENTS

Several GLOF events have occurred over the past few decades in the Himalaya-China region, causing extensive damage to roads, bridges, trekking trials, villages, as well as loss of human life and other infrastructures.

The GLOFs have caused extensive damage to major infrastructures. The main processes and the degree of hazard and destruction from the glacial lake outburst cases, based on literature and field investigations, are presented in the Chapter 10.

Chapter 3

Hydro-Meteorology of the Himalaya-China Region

3.1 GENERAL CHARACTERISTICS

There are eight river basins including Pumqu, Rongxer, Poiqu, Zangbuqin, Jilongcangbu, Majiacangbu, Daoliqu and Jiazhangangge in research area. General descriptions of them are given below:

Pumqu basin (Arun)

Pumqu river basin is situated in the southwest of Tibet between the latitude 27º49´N to 29º05´and longitude 85º38´E to 88º57´E. It is bordered by the upriver of the NianChu river and Doqeen Co in the east; and Rongxerzangbo, Bo Qu and Paikuu Co in the west; and Nepal, Sikkim in the south; and YarLungzangbo basin in the north. The total catchments area is 24272 km^2. It is about 320 km in length from east to west and 120 km in breadth from north to south. It originates from the YeBokangjiale glacier of XiXiabama Mountain.

There are many tributaries (YairuZangbo, LoloQu and ZhagarQu) in Pumqu basin. Among these rivers, the catchments area is more than 1000 km^2.

Rongxer basin (Tama Koshi)

Rongxer basin (Tama Koshi basin) is situated in the southwest of Tibet between the latitudes 27°56'N to 28°16'and longitudes 86°07'E to 86°32'E. It originates from the DuokaPula Mountain which elevation is about 5611m. There are so many glaciers at the source of the river. The total catchments area is 1439 km^2. Among the area, the glacial area is about 324.09 km^2. The main river course is about 45 km in length.

Poiqu basin (Bhote-Sun Koshi)

Poiqu basin is situated in the southwest of Tibet between the latitudes 27°55'N to 28°30'and longitudes 85°43'E to 86°18'E. It originates from the Poiqu Co glacier of the south slope of the Himalayan Mountain. The elevation of the river source is about 5320 m and 2000 m at the mouth. It starts from the source of the river flowing from east to west and with the joining of tributaries; it changes the direction near the Nielamu. It enters Nepal and named Bhote-Sun Koshi River near Nielamu about 7 km from north to south.

There are five branches on the right of the river and four branches on the left in Poiqu basin. It is about 80 km in length and the total catchments area is 1990 km^2. Among the area, the glacial area is about 231.58 km^2.

3.2 HYDRO-METEOROLOGICAL OBSERVATION

There are only two meteorological stations-Nielamu and Tingri (shegar) in the research region. 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 analysis the climate of basin. Characteristics of these parameters are discussed as the follow paragraphs. Because there are few observed data in the research basin, so we can only do a trend analysis with station which in the research area.

Air Temperature

These years, with the global warming, which is caused by greenhouse effect, 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 rising and water level of the glacial lakes is changing. Here is an analysis for the research basin reveals a clear increase in temperature after 1990s (Figure 3.1). The trends are accelerated after 1998. We can describe the climate characteristics of the research area with the data of Nielamu and Tingri meteorological station. The research area belongs to semi-humid region. The data of the Nielamu meteorological station: The annual mean temperature is 3.5°. The lowest month mean temperature is -3.7° which occurred in January. The highest month mean temperature is 10.4° which occurred in July. The highest temperature is 22.4° and the lowest one is -20.6°. The temperature data of Tingri station show same warm trend (Figure 3.3).

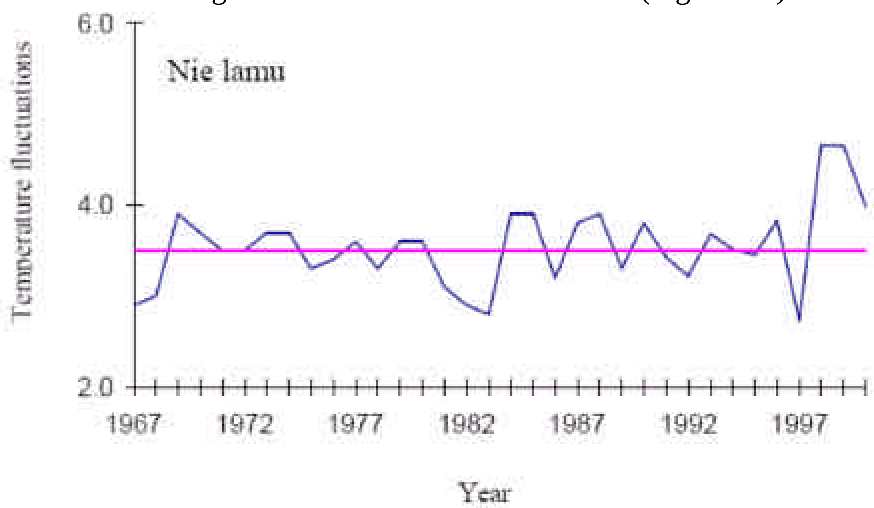


Figure 3.1: Annual temperature trends for the research regions

Precipitation

The research area is situated at the upstream of the Ganges and the North slope of the Himalayan Mountain. It is also the main vapor passage, which the southwestern monsoon going into the mountainous region of western of Tibet. So the precipitation in this area is dominated by a southwestern monsoon, the rainfall decrease from south to north. The maximum precipitation is about 3000mm in the south and 500mm in the north.

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 Ding Ri 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.

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

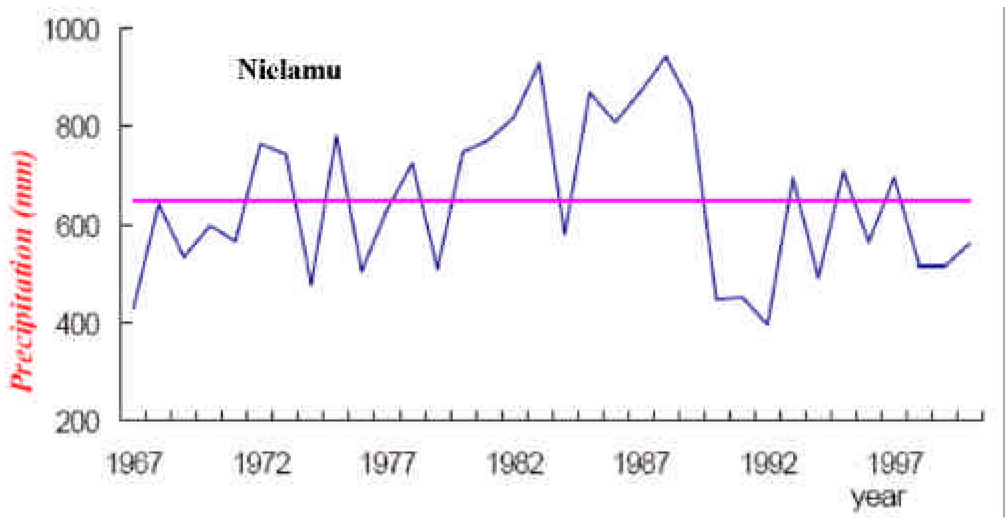


Figure3.2 Annual precipitation trends of Nielamu station

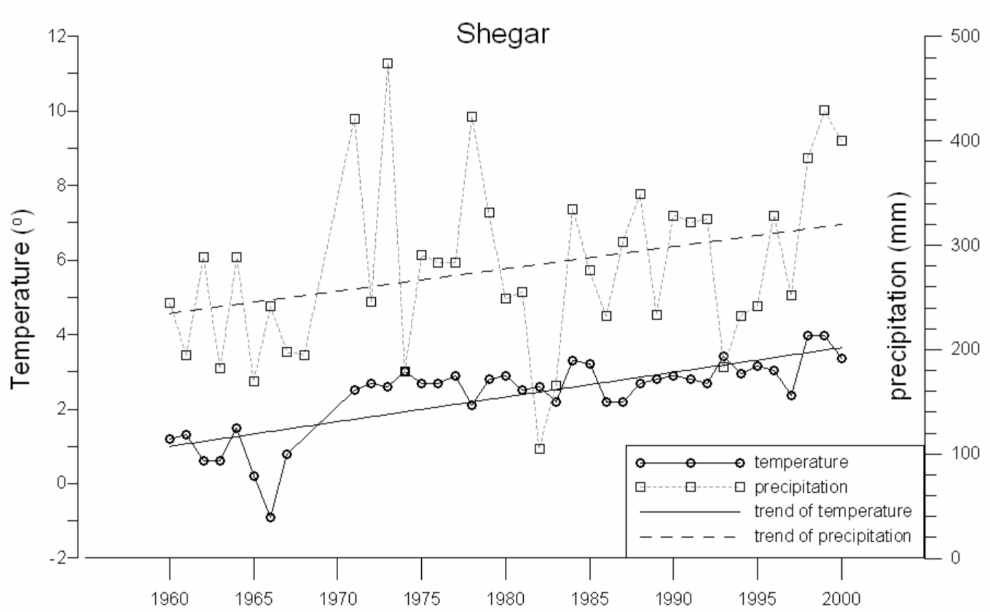


Figure 3.3 Annual precipitation and temperature trends of the Tingri station

Evaporation

Evaporation plays a very important role in water balance. Evaporation is influenced by temperature, humidity, solar radiation, and wind speed. The evaporation increase from south to north: La zi is 2800mm, Tingri is 2550mm, and Nielamu 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

Because much of the river in Himalaya-China region originate from modern glaciers, and many glaciers such as Rong bu glacier distribute around it. Glaciers and snow area is about 25%. The supply runoff belongs to groundwater mix with snowmelt and precipitation. Annual mean runoff is about 50*108 stere.

Here is an analysis for La zi hydrological station: 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.

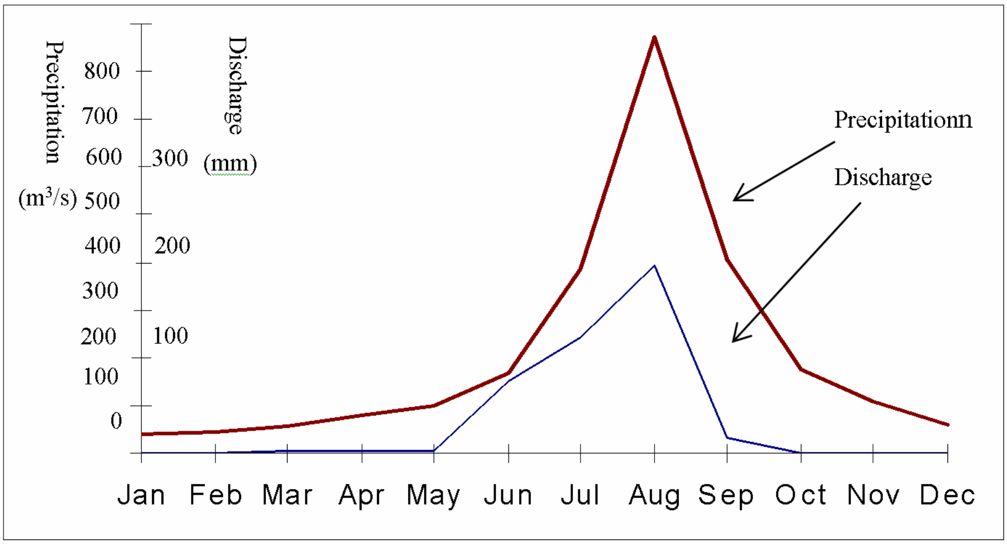


Figure3.4: Hydrograph of discharge and precipitation of La zi station

3.3 CONCLUSION

The GLOF events have been occurred in Tibet especially the period from 1998 to now. The analysis result of Pumqu River basin show that runoff has a increasing trend from 1990s to now; the temperature are growing up; snowmelt increasing and the trend of precipitation is similar to the temperature. Obviously, there is a very important role played in analysis the flood by snow and ice melt in the basin. We should pay close attention to the effect of global warming on the regional hydrology. Particularly, the basin just like Pumqu and Poiqu that distribute a lot of glaciers, it needed real-time monitoring, which will reduce the hazard to the minimum.

Chapter 4

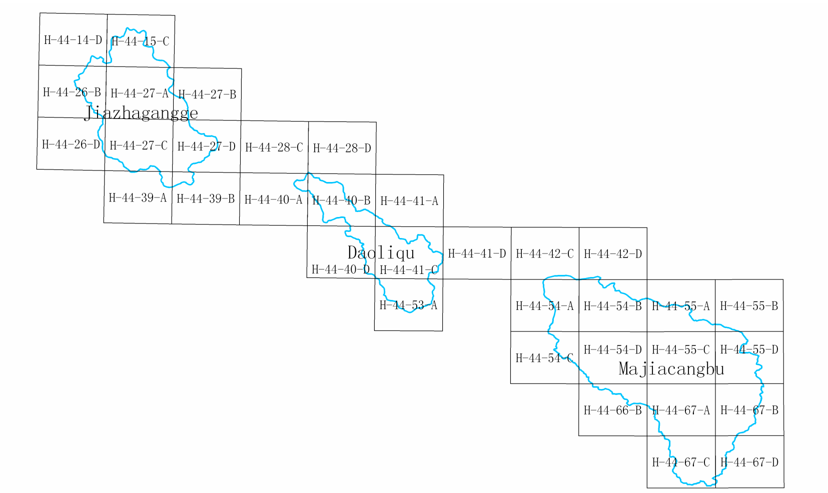
Materials and Methodology

The basic materials required for this research are satellite images, large-scale topographic maps and the inventory of glacier and glacial lakes. The TM image acquired in the 1990 and the ETM image obtained in 2000 were used to study the activity of glaciers and for the identification of potentially dangerous glacial lakes. The topographic maps as reference used to help interpreting image and obtaining some attribute of glaciers such as elevation, orientation.

Remote-sensing data like those from the Land Observation Satellite (Landsat) Thematic Mapper (TM), Indian Remote Sensing satellite series 1D (IRS 1D), Linear Imaging and Self-scanning Sensor (LISS3), and the Système Probatoire d'Observation de la Terre (SPOT) Multispectral (XS) for different dates are also used to study the activity of glaciers and for the identification of potentially dangerous glacial lakes. The combination of digital satellite data and the Digital Elevation Model (DEM) is also used for better and more accurate results for the inventory of glaciers and glacial lakes.

4.1 TOPOGRAPHIC MAPS

The topographic maps used were published in the 1980s (Figure 4.1). There are 148 topographic maps on a scale of 1:50 000 used as reference. Figure 4.1 shows the coverage of topographic maps.



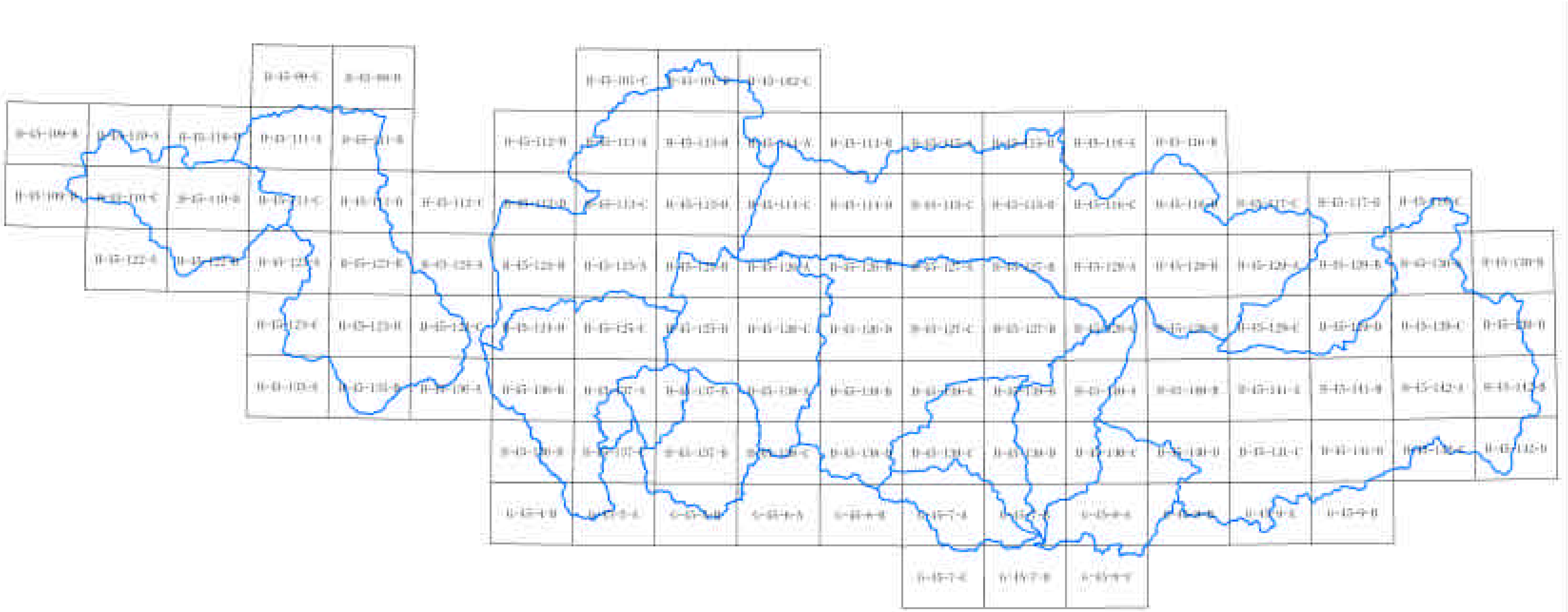


Fig 4.1: index map of topographic maps of the study area

4.2 SATELLITE IMAGES

The satellite data includes TM and ETM images of Landsat, which covered the all research region. Various types of satellite image suitable for the present study are available from different organizations, institutes, and data providers. Due to higher spatial resolutions and relative low costs, the TM and ETM image are acquired as the data source with least cloud cover. The coverage of remote sensing image are shown in figure 4.2. The detailed information about the TM and ETM are explained in Chapter 6.

Fig4.2: Index Map of Landsat ETM images

4.3 INVENTORY OF GLACIERS AND GLACIAL LAKES

The inventory of glaciers published in 2002 and the inventory of glacial lakes made in 1987 are used to partly obtain some attribute of digitized glacier and glacial lake in the topographic maps. Because the inventory of glacier was based on the same topographic maps, there is no large difference to cite the data of inventory.

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) and the methodology for the inventory of glacial lakes is based 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). The inventory of glaciers and glacial lakes has been systematically carried out for the drainage basins on the basis of topographic maps and aerial photographs. Topographic maps at scale of 1:50000 published during the period from the 1970s to the 1980s are used.

The following sections describe how the compilation of the inventories for both the glaciers and glacial lakes has been carried out.

4.3.1 Inventory of glaciers

The glacier margins

The glacier margins on each topographic map are delineated and compared with aerial photographs, and the exact boundaries between glaciers and seasonal snow cover are determined. The coding system is based on the subordinate relation and direction of river progression according to the World Glacier Inventory (WGI). The descriptions of attributes for the inventory of glaciers are given below.

Numbering of glaciers

The lettering and numbering start from the mouth of the major stream and proceed clockwise round the basin. For convenience, the major river systems are further divided into five levels sub-basins.

For example, "5" indicate Asia, " Z " indicate the inner-land water system of Qingzang plateau (level 1 basin),"2"indicate the selincuo lake basin(level 2 basin). The coding of level 3 and level 4 basin is in Arabic numerals. As for the level 5 basin, the English letter is used. "**5Z211F1"** indicates Asia, inner-land water system of Qingzang plateau (level 1 basin), Selincuo lake basin (level 2 basin), Chibuzhang lake (level 3 basin), Jinxiwulan lake (level 4 basin), Xianche River (level 5 basin), and the last number indicate the glacial number in the last level basin.

Registration of snow and ice masses

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

Delineation of visible ice, firn, and snow from rock and debris surfaces for an individual glacier does affect various inventory measurements. Marginal and terminal moraines are also included if they contain ice. The 'inactive' ice apron, which is frequently found above the head of the valley glacier, is regarded as part of the valley glacier. Perennial snow patches of large enough size are also included in the inventory. Rock glaciers are included if there is evidence of large ice content.

Snow line

In the present study, the snow line specially refers to the **firn line** of a glacier, not the equilibrium line. The elevation of the firn line of most glaciers was not measured directly but estimated by indirect methods. For the regular valley and cirque glaciers from topographical maps, Hoss's method (i.e. studying changes in the shape of the contour lines from convex in the **ablation area** to concave in the **accumulation area**) was used to assess the snow line.

Accuracy rating table

The accuracy rating table proposed by Muller et al. (1977) on the basis of actual measurements is used in the present study. For the snow line an error range of 50-100m in altitude is entered as an **accuracy rating** of '3'.

Table 4.1 Accuracy rating adopted from Muller et al. (1977)

Index	Area/length (%)	Altitude (m)	Depth (%)
1	0-5	0-25	0-5
2	5-10	25-50	5-10
3	10-15	50-100	10-20
4	15-25	100-200	20-30
5	>25	>200	>30

Mean glacier thickness and ice reserves

According to Muller et al. (1977), mean depth can be estimated with the appropriate model developed for each area by local investigators.

For example, the following model was used for the Swiss Alps

$$\bar{h} = a + b\sqrt{F}$$

where h is the mean depth (m), F is the total surface area (km^2), and a and b are arbitrary parameters that are empirically determined.

There are no measurements of glacial ice thickness for the Himalaya-China regions. Measurements of glacial ice thickness in the Tianshan Mountains, China, show that the glacial thickness increases with the increase of its area (LIGG/WECS/NEA 1988). The relationship between ice thickness (H) and glacial area (F) was obtained there as

$$H = -11.32 + 53.21\,F^{0.3} \qquad \text{if } F >= 0.03\text{km}^2$$

This formula has been used to estimate the mean ice thickness in the glacier inventory. The same method is also used here to find the ice thickness. The ice reserves are estimated by mean ice thickness multiplied by the glacial area.

Area of the glacier

The area of the glacier is divided into accumulation area and ablation area (the area below the firn line). The area is given in square kilometres. The delineated glacier area is measured by the digital planimeter and checked repeatedly. But in this study, we digitized the glaciers with Arcview software and automatically re-calculated the area and ice reserve.

Length of the glacier

The length of the glacier is divided into three columns: **total length**, **length of ablation** and the **mean length**. The total (maximum) length refers to the longest distance of the glacier along the centerline. The mean value of maximum lengths of glacier tributaries (or firn basins) is the mean length.

Mean width

The mean width is calculated by dividing the total area (km^2) by the mean length (km).

Orientation of the glacier

The orientation of accumulation and ablation areas is represented in1 eight cardinal directions (N, NE, E, SE, S, SW, W, and NW). Some of the glaciers are capping just in the form of an apron on the peak, which is inert and sloping in all directions, is represented as ‘360’. The orientations of both the areas (accumulation and ablation) are the same for most of the glaciers.

Elevation of the glacier

Glacier elevation is divided into **highest elevation** (the highest elevation of the crown of the glacier), **mean elevation** (the arithmetic mean value of the highest glacier elevation and the lowest glacier elevation) and **lowest elevation**.

Morphological classification

The morphological matrix-type classification and description is used in the inventory, which was proposed by Muller et al. (1977) for the TTS to the WGI. Each glacier is coded as a six-digit number, the six digits being the vertical columns of Table 4.2. The individual numbers for each digit (horizontal row numbers) must be read on the left-hand side. This scheme is a simple key for the classification of all types of glaciers all over the world.

Each glacier can be written as a six-digit number following Table 4.2. For example, '520110' represents '5' for a valley glacier in the primary classification, '2' for compound basins in Digit 2, '0' for normal or miscellaneous in frontal characteristics in Digit 3, '1' for even or regular in longitudinal profile in Digit 4, '1' for snow and/or drift snow in the major source of nourishment in Digit 5, and 0 for uncertain tongue activity in Digit 6.

The details for the glacier morphological code values according to TTS are explained below.

Digit 1 Primary classification

0 ***Miscellaneous***: Any not listed.
1 ***Continental ice sheet***: Inundates areas of continental size.
2 ***Ice field***: More or less horizontal ice mass of sheet or blanket type of a thickness not sufficient to obscure the sub-surface topography. It varies in size from features just larger than glacierets to those of continental size.
3 ***Ice cap***: Dome-shaped ice mass with radial flow.
4 ***Outlet glacier***: Drains an ice field or ice cap, usually of valley glacier form; the catchment area may not be clearly delineated (Figure 4.3a).
5 ***Valley glacier***: Flows down a valley; the catchment area is in most cases well defined.
6 ***Mountain glacier***: Any shape, sometimes similar to a valley glacier, but much smaller; frequently located in a cirque or niche.
7 ***Glacieret* and *snowfield***: A glacieret is a small ice mass of indefinite shape in hollows, river beds, and on protected slopes developed from snow drifting, avalanching and/or especially heavy accumulation in certain years; usually no marked flow pattern is visible, no clear distinction from the snowfield is possible, and it exists for at least two consecutive summers.
8 ***Ice shelf***: A floating ice sheet of considerable thickness attached to a coast, nourished by glacier(s), with snow accumulation on its surface or bottom freezing (Figure 4.3b).
9 ***Rock glacier***: A glacier-shaped mass of angular rock either with interstitial ice, firn, and snow or covering the remnants of a glacier, moving slowly down slope. If in doubt about the ice content, the frequently present surface firn fields should be classified as 'glacieret and snowfield'.

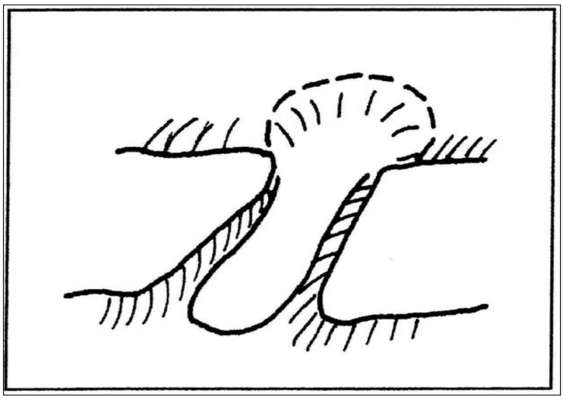
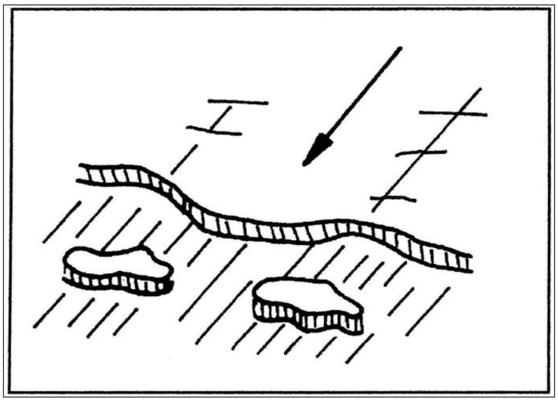
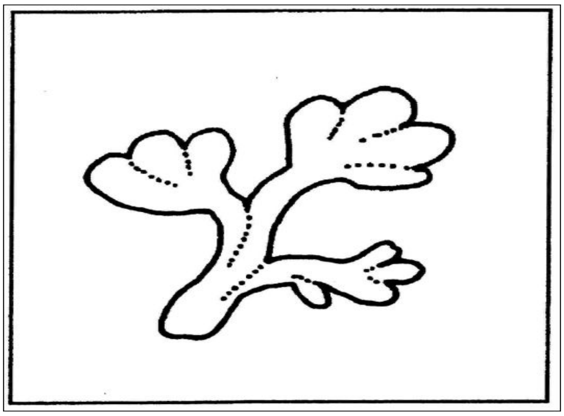
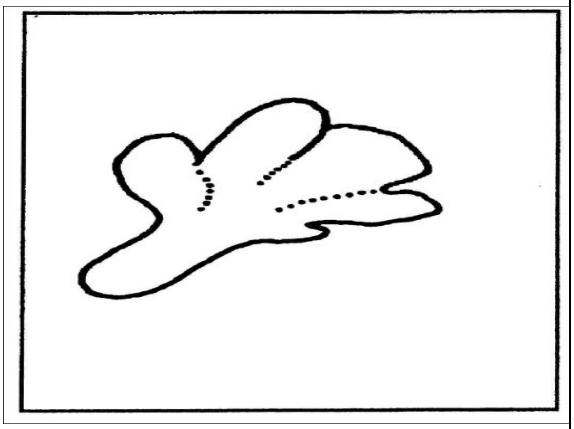
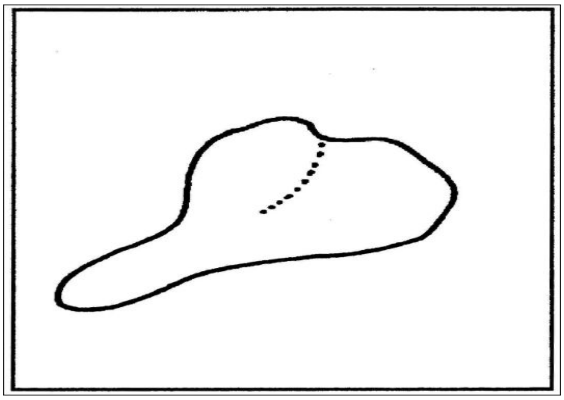
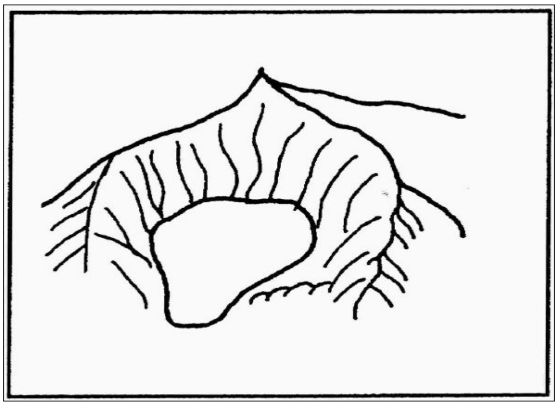
Digit 2 Form

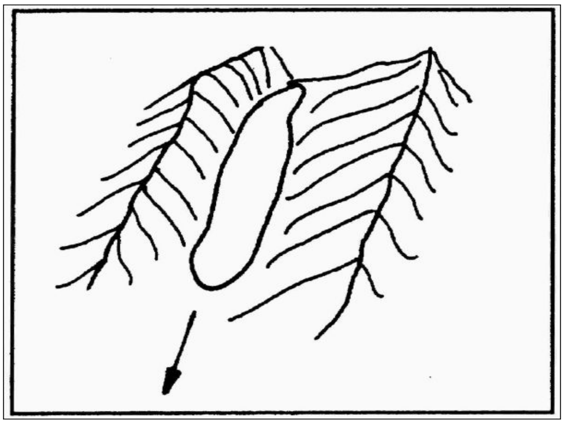
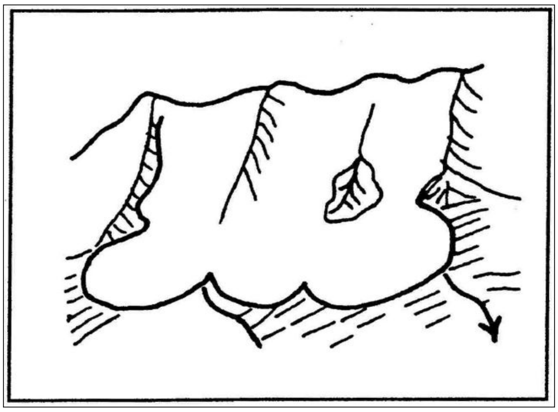
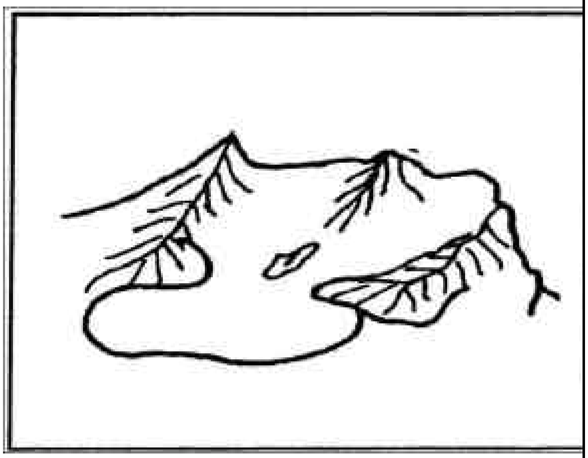
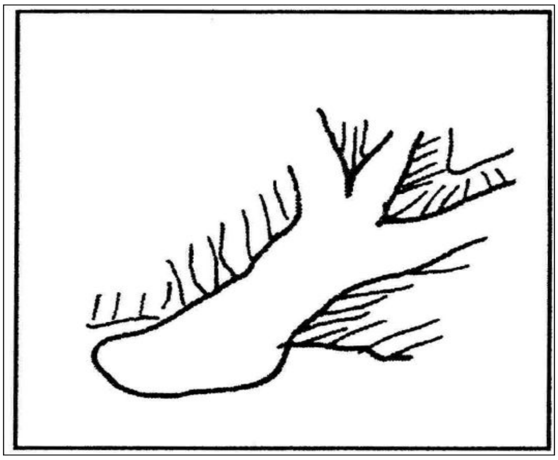
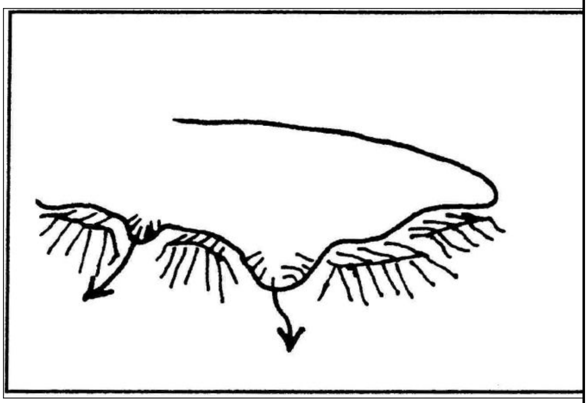
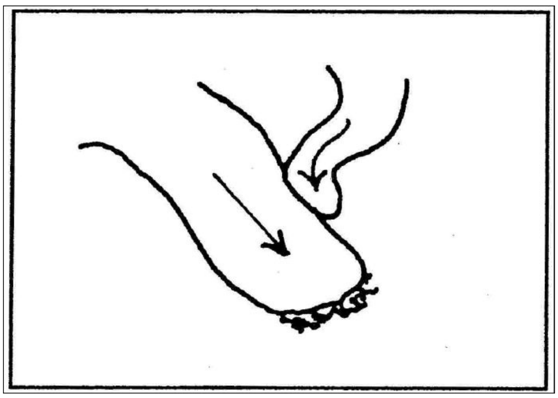
1 ***Compound basins***: Two or more tributaries of a valley glacier, coalescing (Figure 4.4a).
2 ***Compound basin***: Two or more accumulation basins feeding one glacier (Figure 4.4b).
3 ***Simple basin***: Single accumulation area (Figure 4.4c).
4 ***Cirque***: Occupies a separate, rounded, steep-walled recess on a mountain (Figure 4.4d).
5 ***Niche***: Small glacier formed in initially a V-shaped gully or depression on a mountain slope (Figure 4.4e).
6 ***Crater***: Occurring in and /or on a volcanic crater
7 ***Ice apron***: An irregular, usually thin ice mass plastered along a mountain slope.

8 ***Group***: A number of similar ice masses occurring in close proximity and too small to be assessed individually.

9 ***Remnant***: An inactive, usually small ice mass left by a receding glacier.

Table 4.2: Classification and description of glaciers						
	Digit 1	Digit 2	Digit 3	Digit 4	Digit 5	**Digit 6**
	Primary classification	Form	Frontal characteristic	Longitudinal profile	Major source of nourishment	**Activity of tongue**
0	**Uncertain or miscellaneous**	**Uncertain or miscellaneous**	**Normal or miscellaneous**	**Uncertain or miscellaneous**	**Uncertain or miscellaneous**	**Uncertain**
1	**Continental ice sheet**	**Compound basins**	**Piedmont**	**Even: regular**	**Snow and/or drift snow**	**Marked retreat**
2	**Ice field**	**Compound basin**	**Expanded foot**	**Hanging**	**Avalanche and/or snow**	**Slight retreat**
3	**Ice cap**	**Simple basins**	**Lobed**	**Cascading**	**Superimposed ice**	**Stationary**
4	**Outlet glacier**	**Cirque**	**Calving**	**Ice fall**		**Slight advance**
5	**Valley glacier**	**Niche**	**Confluent**	**Interrupted**		**Marked advance**
6	**Mountain glacier**	**Crater**				**Possible surge**
7	**Glacieret and snow field**	**Ice apron**				**Known surge**
8	**Ice shelf**	**Group**				**Oscillating**
9	**Rock glacier**	**Remnant**				

 Figure 4.3a: Outlet	 Figure 4.3b: Ice shelf
 Figure 4.4a: Compound basin	 Figure 4.4b: Compound basin
 Figure 4.4c: Simple basin	 Figure 4.4d: Cirque

 Figure 4.4e: Niche	 Figure 4.5a: Piedmont
 Figure 4.5b: Piedmont	 Figure 4.5c: Expanded
 Figure 4.5d: Lobed	 Figure 4.5e: Confluent

Digit 3 Frontal characteristics

1 ***Piedmont***: Ice field formed on low land with the lateral expansion of one or the coalescence of several glaciers (Figures 4.5 a and b).
2 ***Expanded foot***: Lobe or fan of ice formed where the lower portion of the glacier leaves the confining wall of a valley and extends on to a less restricted and more level surface. Lateral expansion markedly less than for Piedmont (Figure 4.5c).
3 ***Lobed***: Tongue-like form of an ice field or ice cap (see Figure 4.5d)
4 ***Calving***: Terminus of glacier sufficiently extending into sea or occasionally lake water to produce icebergs.
5 ***Confluent***: Glaciers whose tongues come together and flow in parallel without coalescing (Figure 4.5e).

Digit 4 Longitudinal profile

1 ***Even /regular***: Includes the regular or slightly irregular and stepped longitudinal profile.
2 ***Hanging***: Perched on a steep mountain slope, or in some cases issuing from a steep hanging valley.
3 ***Cascading***: Descending in a series of marked steps with some crevasses and seracs.
4 ***Ice fall***: A glacier with a considerable drop in the longitudinal profile at one point causing a heavily broken surface.
5 ***Interrupted***: Glacier that breaks off over a cliff and reconstitutes below.

Digit 5 Major source of nourishment

The sources of nourishment could be uncertain or miscellaneous (0), snow and/or drift snow (1), avalanche and/or snow (2), or superimposed ice (3) as indicated in Table 4.2.

Digit 6 Activity of tongue

A simple-point qualitative statement regarding advance or retreat of the glacier tongue in recent years, if made for all glaciers on Earth, would provide the most useful information. The assessment of an individual glacier (strongly or slightly advancing or retreating etc) should be made in terms of the world picture and not just that of the local area; however, it seems very difficult to establish the quantitative basis for the assessment of the tongue activity. A change of frontal position of up to 20m per year might be classed as ‘slight’ advance or retreat. If the frontal change takes place at a greater rate it would be called ‘marked’. Very strong advances or surges might shift the glacier front by more than 500m per year. Digit 6 expresses qualitatively the annual tongue activity. If observations are not available on an annual basis then an average annual activity is given.

Moraines: Two digits to be given.

Digit 1*:* moraines in contact with present-day glacier.

Digit 2*:* moraines further downstream.

0 no moraines
1 terminal moraine
2 lateral and/or medial moraine
3 push moraine
4 combination of 1 and 2
5 combination of 1 and 3

6 combination of 2 and 3
7 combination of 1, 2, and 3
8 debris, uncertain if morainic
9 moraines, type uncertain or not listed.

Remarks: The remarks can, for instance, consist of the following information.

- Critical comments on any of the parameters listed on the data sheet (e.g. how clos e is the snow line to the firn line, comparison of year concerned with other years).
- Special glacier types and glacier characteristics which, because of the nature of the classification scheme, are not described in sufficient detail (e.g. 'melt structures', glacier-dammed lakes).
- Additional parameters of special interest to the basins concerned (e.g. area of altitudinal zones, inclination etc).
- It is often useful to divide the snow line into several sections (because of different exposition or nourishment). In such cases, the snow line data of each section can be recorded separately.
- Literature on the glacier concerned.
- Any other remarks

The inventory database form (see Annex I and ?) used for compilation of the inventory of glaciers includes basin numbers, map/satellite codes and year, as well as the glacier parameters described above.

4.3.2 Inventory of glacial lakes

The glacial lakes on each image are delineated by the help of DEM. The descriptions of attributes for the glacial lakes' inventory based on LIGG, WECS and NEA (1988) are given below.

Numbering of glacial lakes

The numbering of the lakes starts from the outlet of the major stream and proceeds clockwise rounding the basin.

Longitude and latitude

Reference longitude and latitude are designated for the approximate centre of the glacial lake.

Area

The area of the glacial lake is determined from the digital database after digitization of the lake from the topographic maps.

Length

The length is measured along the long axis of the lake, and estimated to one decimal place in km units (0.1 km).

Width

The width is normally calculated by dividing the area by the length of the lake, down to one decimal place in km units (0.1 km).

Depth

The depth is measured along the axis of the cross section of the lake. On the basis of the depth along the cross section the average depth and maximum depth are estimated. The data are collected from the literature.

Orientation

The drainage direction of the glacial lake is specified as one of eight cardinal directions (N, NE, E, SE, S, SW, W, and NW). For a closed glacial lake, the orientation is specified according to the direction of its longer axis.

Altitude

The altitude is registered by the water surface level of the lake in masl.

Classification of lakes

Genetically glacial lakes can be divided into the following.

- Glacial erosion lakes, including cirque lakes, trough valley lakes, and erosion lakes.
- Moraine-dammed lakes (also divided into neo end moraine and paleo end moraine lakes), include end moraine lakes and lateral moraine lakes.
- Blocking lakes formed through glaciers and other factors, including the main glacier blocking the branch valley, the glacier branch blocking the main valley, and the lakes formed through snow avalanche, collapse, and debris flow blockade.
- Ice surface and sub-glacial lakes.

In the glacial lake inventory, end moraine-dammed lakes, lateral moraine lakes, trough valley lakes, glacial erosion lakes, and cirque lakes are represented by the letters M, L, V, E, and C respectively; B represents blocking lakes.

Activity

According to their stability, the glacial lakes are divided into three types: stable, potential danger, and outburst (when there have been previous bursts). The letters S, D, and O represent these types respectively.

Types of water drainage

Glacial lakes are divided into drainage lakes and closed lakes according to the drainage pattern. The former refers to lakes from which water flows to the river and joins the river system. In the latter, water does not flow into the river. Ds and Cs represent those two kinds of glacial lakes respectively.

Chemical properties

This attribute is represented by the degree of mineralisation of the water, mg l^{-1}.

Other indices

One important index for evaluating the stability of a glacial lake is its contact relation with the glacier. So an item of distance from the upper edge of the lake to the terminus of the glacier has been added and the code of the corresponding glacier registered. Since an end moraine-dammed lake is related to its originating glacier, this index is only referred to end moraine-dammed lakes. As not enough field data exist, the average depth of glacial lakes is difficult to establish in most cases. Based on field data, and as an indication only, the average depth of a glacial lake formed by different causes can be roughly estimated as follows: cirque lake, 10m; lateral moraine lake, 30m; trough valley lake, 25m; blocking lake and glacier erosion lake, 40m; lateral moraine lake, 20m. The water reserves of different types of glacial lakes can be obtained by multiplying their average depth by their area (LIGG/WECS/NEA 1988).

The inventory database form (see Annex II) used for compilation of the inventory of glacial lakes includes basin numbers, map/satellite image codes and year, as well as the lake parameters (attributes) described above.

Chapter 5

Spatial Data Input and Attribute Data Handling

One of the main objectives of the present study is to develop a digital database of glaciers and glacial lakes using GIS. A digital database is necessary for the monitoring of glaciers and glacial lakes and to identify the potentially dangerous lakes. GIS is the most appropriate tool for spatial data input and attribute data handling. It is a computer-based system that provides the following four sets of capabilities to handle geo-referenced data:

- data input,
- data management (data storage and retrieval),
- data manipulation and analysis, and
- data output

Any spatial features of the earth's surface are represented in GIS by the following:

- **area/polygons**: features which occupy a certain area, e.g. glacier units, lake units, land-use units, geological units etc;
- **lines/segments**: linear features, e.g. drainage lines, contour lines, boundaries of glaciers and lakes etc;
- **points**: points define the discrete locations of geographic features, the areas of which are too small to illustrate as lines or polygons, e.g. mountain peaks or discrete elevation points, sampling points for field observations, identification points for polygon features, centres of glaciers and lakes etc, and attribute data refer to the properties of spatial entities.

The spatial entities described above can be represented in digital form by two data models: vector or raster models. In a vector model the position of each spatial feature is defined by a series of *X* and *Y* coordinates. Besides the location, the meaning of the feature is given by a 'code'. In a raster model, spatial data are organized in grid cells or pixels, a term derived for a picture element. Pixels are the basic units for which information is explicitly recorded. Each pixel is assigned only one value.

For the present study, ENVI is used for precise geometric-correction, and Arcview3.0/Arcgis 8.0 for Windows is used for the spatial and attribute database development and analysis. ENVI is a special image-processing software, and Arcview3.0/Arcgis 8.0 for Windows is a geographic information system developed by ESRI (Environmental Systems Research Institute, Inc.). Analysis and modeling in a GIS requires input of relevant data. Eight scenes of TM images acquired in 1990 are the baseline to research the glacier change. The topographic maps on a scale 1:50,000 published in 1980s were used as reference to obtaining the spatial data of glaciers and glacial lakes. The ETM+ images acquired in 2000 were used as the base-map for second period. The list of topographic maps and RS images used for the study is given in Chapter 4. All the glaciers and glacial lakes were numbered and their attributes were inputted or computed. The details of the coding for the glacier and glacial lakes are given in detail in Chapter 4.

To compare change between different periods, we must co-register RS images supported by ENVI in order to correctly match each other. The correction precision is less than one pixel. Then, referenced with the corrected topographic maps, we choose the obvious objects with the same name in the RS images to correct it.

The most common method of entering spatial data is manual digitizing by using ArcView. It is always necessary to maintain the details, smoothness and accuracy of the input spatial data of all the glaciers and glacial lakes as in the maps of the given map scale. Before starting digitization one should know the map projection system. A map projection defines the relationship between the map coordinates and the geographic coordinates (latitude and longitude). The topographic maps are in Gauss-Kruger projection, and the Himalaya-China regions are situated in the 44th and 45th projection-zone.

All the polygons representing glaciers and glacial lakes are numbered as mentioned in Chapter 4. Label Points showing the location of glaciers and glacial lakes were set up in the ArcInfo. They were used later for identification of the polygons of the glaciers and glacial lakes. After digitization, the segments were checked and the glaciers and glacial lakes were numbered using point identifiers. But there is exception instance, some glaciers existed in the topographic maps have been divided into independent parts, so we numbered every sub-glacier by adding a numerical suffix to the original code (e.g., 5O191A0007-1, 5O191A0007-2).

In GIS, polygon maps with identifier domains of the objects have a related attribute table with the same domain. The domain defines the possible contents of a map, a table, or a column in a table (attribute). Some examples of 'domain' are class domain (a list of class names), value domain (measured, calculated, or interpolated values), image domain (reflectance values in a satellite image or scanned aerial photograph), identifier domain (a unique code for each item in the map), string domain (columns in a table that contain text), bit domain (value 0 and 1), etc. An attribute table is linked to a theme through its ID. An attribute table can only be linked to a theme with a unique identifier domain. An attribute table may contain several columns. Each column corresponds to a feature (such as point, line, polygon) in the theme.

The required attributes of the glaciers and glacial lakes were derived or entered in the attribute database in the GIS. Attributes such as area, location (latitude, longitude), length were derived from the spatial database. If other necessary digital spatial data layers, such as digital elevation models (DEM), are available, it is possible to generate terrain parameters such as elevation, slope, length as measuring units for glaciers and glacial lakes. Other attributes, such as orientation, elevation, map code, name were manually entered in the attribute database. Additional attributes, such as mean elevation, ice reserves were derived using logical calculations. Some of the attributes were also derived from the results of an aggregation in the same table or from another table using the table joining operations, such as glaciers associated with the glacial lakes, glacier length etc. The attribute database for glaciers and glacial lakes is given in the annexes.

The analysis for the change of glacier and the criteria for the identification of potentially dangerous glacial lakes are explained in Chapter 11. Using the logical calculation in the GIS, the activity of glacier and potentially dangerous glacial lakes were determined. To study the geomorphic characteristics of these potentially dangerous lakes, time-series of satellite images were used and the potentially dangerous glacial lakes were finally identified (Table 11.9).

Chapter 6

Application of Remote Sensing

Glaciers and glacial lakes are generally located in remote areas, where access must through tough and difficult terrain. The study of glaciers and glacial lakes, as well as carrying out glacial lake outburst flood (GLOF) inventories and field investigations using conventional methods, requires extensive time and resources together with undergoing hardship in the field. Creating inventories and monitoring of the glaciers, glacial lakes and extent of GLOF impacting on downstream can be done quickly and correctly using satellite images and aerial photographs. Use of these images and photographs for the evaluation of physical conditions of the area provides greater accuracy. The multi-stage approach using remotely sensed data and field investigation increases the ability and accuracy of the work. Visual and digital image analysis techniques integrated with GIS techniques are very useful for the study of glaciers, glacial lakes, and GLOFs.

Remote sensing is the science and art of acquiring information (spectral, spatial, and temporal) about material objects, areas, or phenomena through the analysis of data acquired by a device from measurements made at a distance, without coming into physical contact with the objects, area, or phenomena under investigation.

Remote-sensing technology makes use of the wide range of the electro-magnetic spectrum (EMS). Most of the commercially available remote-sensing data are acquired in the visible, infrared, and microwave wavelength portion of the EMS. For the present study, the data acquired within the visible and infrared wavelength ranges were used.

There are different types of commercial satellite data available. Digital data sets of the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER), the Landsat-5 Thematic Mapper (TM) and Landsat-7 Enhanced Thematic Mapper Plus (ETM+) were used mostly for the present study. Some data sets of the China-Brazil Earth Resources Satellite (CBERS) and Indian Remote Sensing Satellite Series 1D (IRS 1D), Linear Imaging and Self Scanning Sensor (LISS) 3 were also used. This study adopts the TM and ETM+ images, the list of the images relevant to the present study are given in Chapter 4.

6.1 THEMATIC MAPPER (TM)

Thematic Mapper (TM) is a multi-spectral scanning radiometer that was carried on board Landsat 5. The TM sensors have provided nearly continuous coverage from July 1984 to present, with a 16-day repeat cycle. TM image data consists of seven spectral bands with a spatial resolution of 30 meters for most bands (1-5 and 7) (see table 6.1). Spatial resolution for the thermal infrared (band 6) during image acquisition is 120 meters, but the delivered TM band 6 will be resampled to 30 meter pixel size. The approximate scene size will be 185 x 185 kilometers.

Table 6.1 The Channel Characteristic of Thematic Mapper (TM)			
	Landsat-5	**Wavelength (mm)**	**Resolution (m)**
Thematic Mapper (TM)	Band 1	0.45-0.52	30
	Band 2	0.52-0.60	30
	Band 3	0.63-0.69	30
	Band 4	0.76-0.90	30
	Band 5	1.55-1.75	30
	Band 6	10.40-12.50	120
	Band 7	2.08-2.35	30

This is a photograph of the Thematic Mapper on the ground before it was mated to the spacecraft. Note the gold leaf that is used to shield the inner workings.

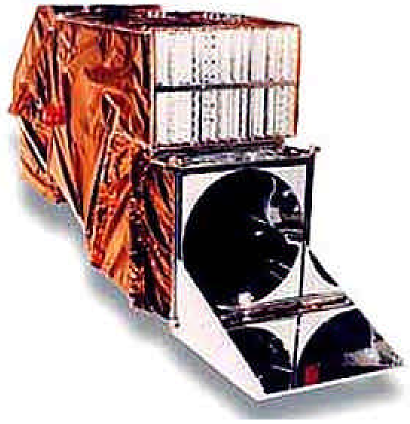


Figure 6.1 The TM Sensor

This cutaway diagram shows the major components of the TM system:

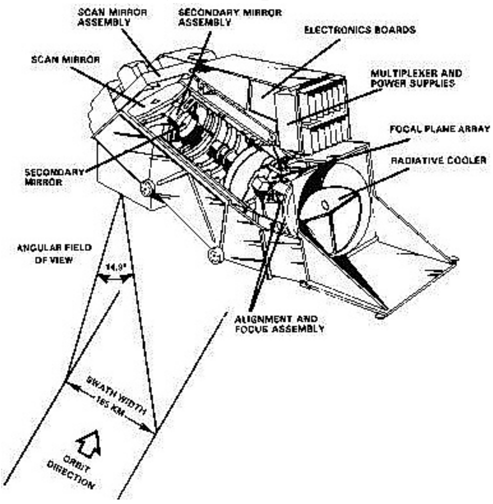


Figure 6.2 The TM System and configuration

The sketch below shows some of the components in the optical train and detector layout of the TM

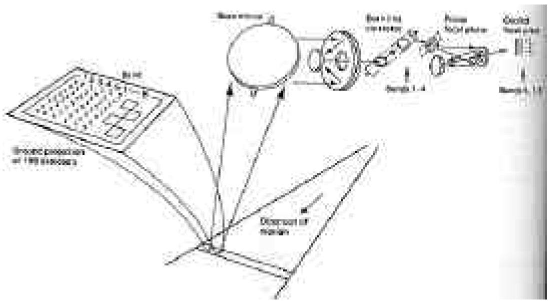


Figure 6.3 The design of TM

Table 6.2 Orbit Characteristics	
Type	Sun Synchronous, polar
Altitude	705 km
Inclination	98.2 degree
Period Recurrent period	98.9 minute 16 days
equatorial crossing time	09:30 am
Swath Width	185 km

6.2 ENHANCED THEMATIC MAPPER PLUS (ETM+)

The Enhanced Thematic Mapper Plus (ETM+) is a multi-spectral scanning radiometer that is carried on board the Landsat 7 satellite. The sensor has provided nearly continuous acquisitions since July 1999, with a 16-day repeat cycle. An instrument malfunction occurred on May 31, 2003, with the result that all Landsat-7 scenes acquired since July 14, 2003 have been collected in "SLC-off" mode.

The ETM+ instrument provides image data from eight spectral bands. The spatial resolution is 30 meters for the visible and near-infrared (bands 1-5 and 7). Resolution for the panchromatic (band 8) is 15 meters, and the thermal infrared (band 6) is 60 meters. The approximate scene size is 185 x 185 kilometers.

Table 6.3 The Channel Characteristic of Enhance Thematic Mapper

Enhance Thematic Mapper (ETM+)	Landsat-7	Wavelength (mm)	Resolution (m)
	Band 1	0.45-0.52	30
	Band 2	0.52-0.60	30
	Band 3	0.63-0.69	30
	Band 4	0.76-0.90	30
	Band 5	1.55-1.75	30
	Band 6	10.40-12.50	120
	Band 7	2.08-2.35	30
	Pan	0.52-0.90	15

Table 6.4 Orbit Characteristics	
Altitude	705 km
Inclination	98.2 degree
Period	98.9 minute
Recurrent period	16 days
equatorial crossing time	10:00 am
Swath Width	185 km

6.3 APPLICATION OF REMOTE SENSING

When electro-magnetic energy is incident on any given earth surface feature, three fundamental energy interactions with the feature are possible. Various fractions of energy incident on the element are reflected, absorbed, and/or transmitted. All components of incident, reflected, absorbed, and/or transmitted energy are a function of the wavelength. The proportions of energy reflected, absorbed, and transmitted vary for different earth features, depending on their material types and conditions. These differences permit us to distinguish different features on an image. Thus, two features may be distinguishable in one spectral range and may be very different on another wavelength band. Within the visible portion of the spectrum, these spectral variations result in the visual effect called color. For example, blue objects reflect highly in the blue portion of the spectrum, likewise green reflects highly in the 'green' spectral region, and so on. Thus, the eye uses spectral variations in the magnitude of reflected energy to discriminate between various objects.

Satellite data are digital records of the spectral reflectance of the Earth's surface features. These digital values of spectral reflectance are used for image processing and image interpretations. A graph of the spectral reflectance of an object as a function of wavelength is called a spectral reflectance curve. The configuration of spectral reflectance curves provides insight into the characteristics of an object and has a strong influence on the choice of wavelength region(s) in which remote-sensing data are acquired for a particular application. Figure 6.4 shows the typical spectral reflectance curves for three basic types of earth feature: green vegetation, soil, and water. The lines in this figure represent average reflectance curves compiled by measuring large sample features. It should be noted how distinctive the curves are for each feature. In general, the configuration of these curves is an indicator of the type and condition of the features to which they apply. Although the reflectance of individual features may vary considerably above and below the average, these curves demonstrate some fundamental points concerning spectral reflectance.

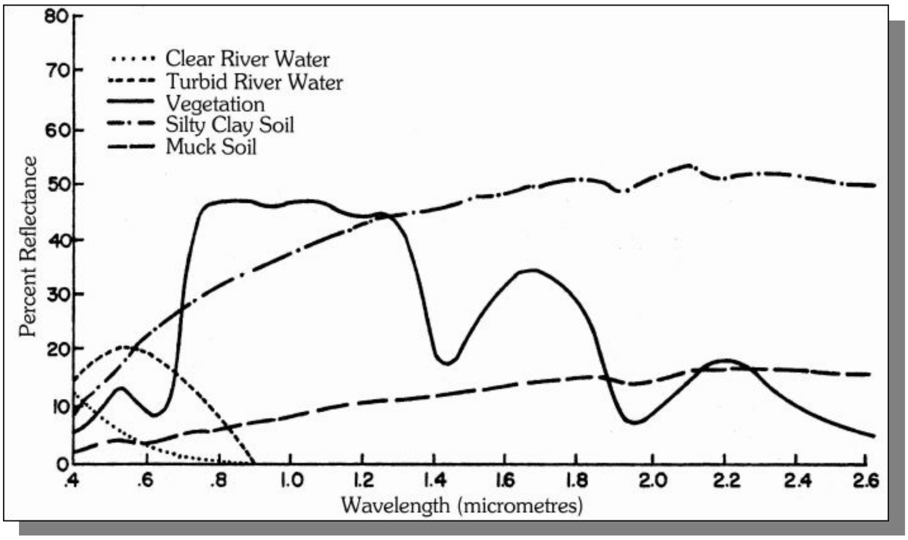


Figure 6.4: Typical spectral reflectance curves for vegetation, soil, and water (after Swain and Davis 1979)

Spectral reflectance curves for vegetation almost always manifest the ‘peak-and-valley’ configuration (Figure 6.4). Valleys in the different parts of the spectral reflectance curve are the result of the absorption of energy due to plants, leaves, pigments, and chlorophyll content at 0.45 and 0.67 µm wavelength bands and water content at 1.4, 1.9, and 2.7 µm wavelength bands. In near infrared spectrum wavelength bands ranging from about 0.7-1.3µm, plants reflect 40-50% of energy incident upon them. The reflectance is due to plant leaf structure and is highly variable among plant species, which permits discrimination between species. Different plant species reflect differently in different portions of wavelength.

The soil curve in Figure 6.4 shows considerably less peak-and-valley variation in reflectance. This is because the factors that influence soil reflectance act over less specific spectral bands. Some of the factors affecting soil reflectance are moisture content, soil texture (proportion of sand, silt, and clay), surface roughness, presence of iron oxide, and organic matter content. These factors are complex, variable, and inter-related. For example, the presence of moisture in soil will decrease its reflectance. As with vegetation, this effect is greatest in the water absorption bands at about 1.4, 1.9, and 2.7 µm (clay soils also have hydroxyl absorption bands at about 1.4 and 2.2 µm). Soil moisture content is strongly related to soil texture; coarse and sandy soils are usually well drained, resulting in low moisture content and relatively high reflectance; poorly drained and fine-textured soils will generally have lower reflectance. In the absence of water, however, the soil may exhibit the reverse tendency, that is, coarse-textured soils may appear darker than fine-textured soils. Thus, the reflectance properties of soil are consistent only within a particular range of conditions. Two other factors that reduce soil reflectance are surface roughness and organic matter content. Soil reflectance normally decreases when surface roughness and organic matter content increases. The presence of iron oxide in soil also significantly decreases reflectance, at least in the visible wavelengths. In any case, it is essential that the analyst be familiar with the existing conditions.

When considering the spectral reflectance of water, probably the most distinctive characteristic is the energy absorption at near infrared wavelengths. Water absorbs energy in these wavelengths, whether considering water features *per se* (such as lakes and streams) or water contained in vegetation or soil. Locating and delineating water bodies with remote-sensing data are carried out easily in near infrared wavelengths because of this absorption property. However, various conditions of water bodies manifest themselves primarily in visible wavelengths. The energy/matter interactions at these wavelengths are very complex and depend on a number of inter-related factors. For example, the reflectance from a water body can stem from an interaction with the water surface (specula reflection), with material suspended in the water, or with the bottom of the water body. Even in deep water where bottom effects are negligible, the reflectance properties of a water body are not only a function of the water *per se* but also of the material in the water.

Clear water absorbs relatively little energy with wavelengths of less than about 0.6 µm. High transmittance typifies these wavelengths with a maximum in the blue-green portion of the spectrum. However, as the turbidity of water changes (because of the presence of organic or inorganic materials), transmittance, and therefore reflectance, changes dramatically. This is true in the case of water bodies in the same geographic area. Spectral reflectance increases as the turbidity of water increases. Likewise, the reflectance of water depends on the concentration of chlorophyll. Increases in chlorophyll concentration tend to decrease water reflectance in blue wavelengths and increase it in green wavelengths. Many important water characteristics, such as dissolved oxygen concentration, pH, and salt concentration, cannot be observed directly through changes in water reflectance. However, such parameters sometimes correlate with observed reflectance. In short, there are many complex inter-relationships between the spectral reflectance of water and its particular characteristics. One must use appropriate reference data to correctly interpret reflectance measurements made over water.

Snow and ice are the frozen state of water. Early work with satellite data indicated that snow and ice could not be reliably mapped because of the similarity in spectral response between snow and clouds due to limitations in the then available data set. Today satellite remote sensing systems' data are available in more spectral bands (eg, Landsat TM in seven bands). It is now possible to differentiate snow and cloud easily in the middle infrared portion of the spectrum, particularly in the 1.55-1.75µm and 2.10-2.35µm wavelength bands (bands 5 and 7 of Landsat TM). In these wavelengths, the clouds have a very high reflectance and appear white on the image, while the snow has a very low reflectance and appears black on the image. In the visible, near infrared, and thermal infrared bands, spectral discrimination between snow and clouds is not possible, while in the middle infrared it is. The reflectance of snow is generally very high in the visible portions and decreases throughout the reflective infrared portions of the spectrum. The reflectance of old snow and ice is always lower than that of fresh snow and clean/fresh glacier in all the visible and reflective infrared portions of the spectrum. Compared to clean glacier and snow (fresh as well as old), debris covered glacier and very old/dirty snow have much lower reflectance in the visible portions of the spectrum and higher in the middle infrared portions of spectrum.

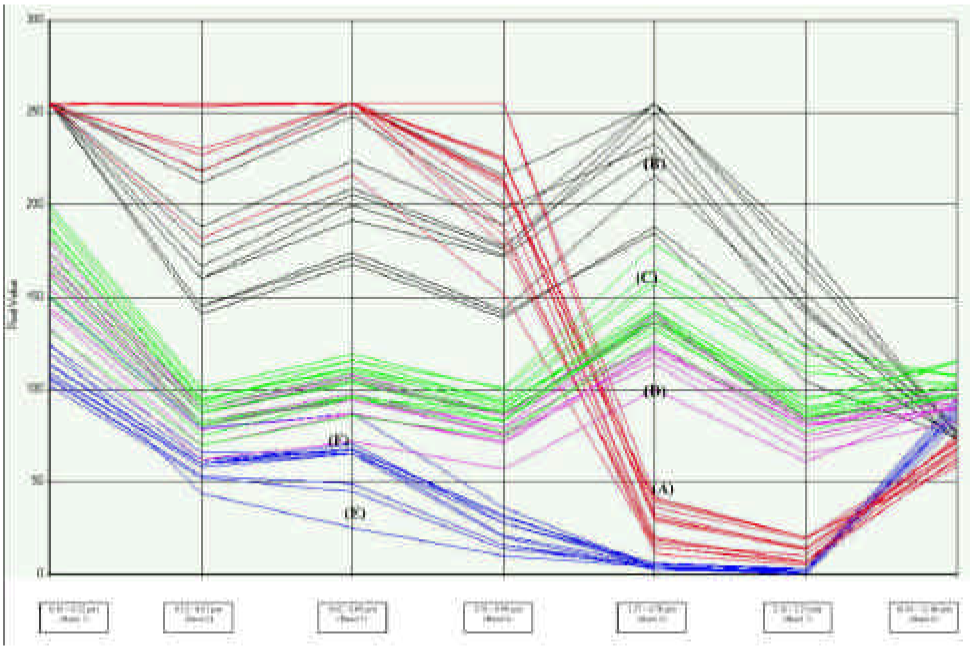


Figure 6.5: Spectral reflectance characteristics of snow/ice, clean glaciers, debris covered glaciers, clouds, and water bodies. Reflectance in terms of pixel value based on a September 22, 1992 Landsat TM seven-band data set of the Tama Koshi and Dudh Koshi areas of Nepal. Red lines-clean glaciers and fresh snow (A); black lines-clouds (B); green lines-recent debris from GLOFs (C); maroon lines-debris covered glacier (D); blue lines-clean/melted (E); and silty and/or partly frozen water (lake) (F)

To identify the individual glaciers and glacial lakes, different image enhancement techniques are useful. However, complemented by the visual interpretation method (visual pattern recognition), with the knowledge and experience of the terrain conditions, glacier and glacial lake inventories and monitoring can be done. With different spectral band combinations in false color composite (FCC) and in individual spectral bands, glaciers and glacial lakes can be identified and studied using the knowledge of image interpretation keys: color, tone, texture, pattern, association, shape, shadow, etc. Combinations of different bands can be used to prepare FCC. Different color composite images highlight different land-cover features.

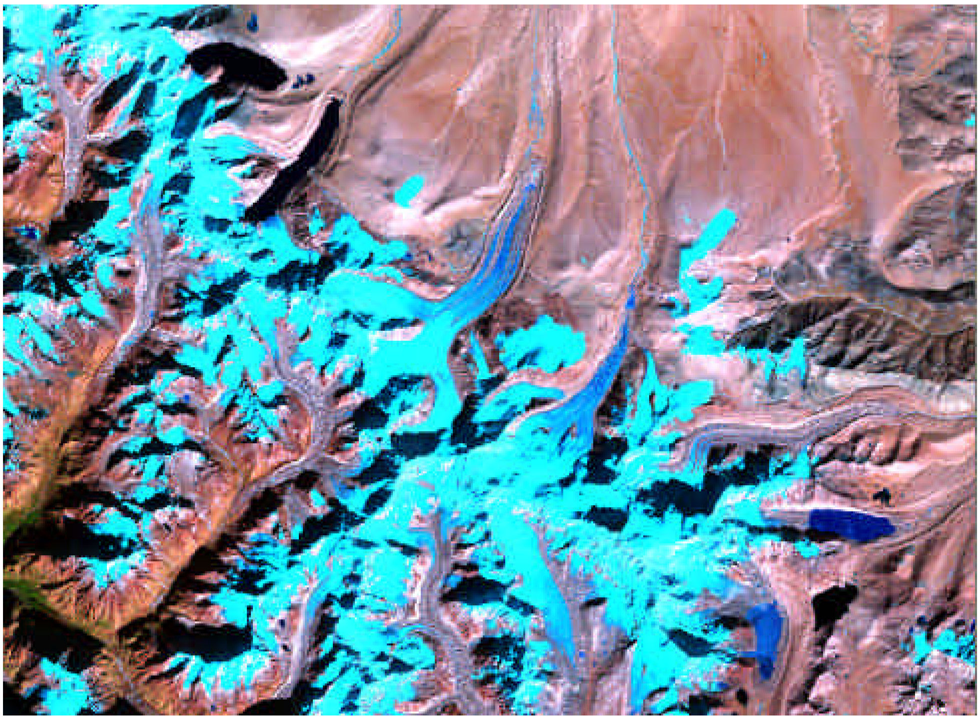


Figure 6.6 The FCC of ETM

Figures 6.6 show color composite images assigning red, green, and blue colors to different bands of ETM image of 22 November 2000. Colors in the colour composite images and tones in the individual band images are the outcome of the reflectance values. Glaciers appear white (in individual bands and colour composite) to light blue (in colour composite) colour of variable sizes, with linear and regular shape having fine to medium texture, whereas, in the thermal band, they appear gray to black. The distinct linear and dendritic pattern associated with slopes and valley floors of the high mountains covered with seasonal snow can be distinguished in the glaciers in the mountains.

The lake water in color composite images ranges in appearance from light blue to blue to black. In the case of frozen lakes, it appears white. Sizes are generally small, having circular, semi-circular, or elongated shapes with very fine texture and are generally associated with glaciers in the case of high lying areas, or rivers in the case of low lying areas. In general, erosion lakes and some cirque lakes are not necessarily associated with glaciers or rivers at present. The debris flow path along the drainage channel gives a white to light gray and bright tone.

For glacier and glacial lake identification from satellite images, the images should be with least snow cover and cloud free. Least snow cover in the Himalayas occurs generally in the summer season (May-September). But during this season, monsoon clouds will block the views. If snow precipitation is late in the year, winter images are also suitable except for the problem of long relief shadows in the high mountain regions. Knowledge of the physical characteristics of the glaciers, lakes, and their associated features is always necessary for the interpretation of the images. For example, the end moraine damming the lake may range from a regular curved shape to a semi-circular crescent shape. The frozen lake and glacier ice field may have the same reflectance, but the frozen lake always has a level surface and is generally situated in the ablation areas of glaciers or at the toe of the glacier tongue, and there is greater possibility of association with drainage features downstream.

The technique of digital image analysis facilitates image enhancement and spectral classification of the ground features and, hence, greatly helps in the study of glaciers and lakes. Monitoring of the lakes and glaciers can be done visually as well as digitally. In both the visual interpretation and digital feature extraction techniques, the analyst's experience and adequate field knowledge are necessary. The satellite images have to be geometrically rectified based on the appropriate geo-reference system and cell sizes. The same geo-reference system is required for the integration and analysis of the remote sensing satellite data in the GIS database for better results.

The lakes that have already burst in the past can be identified from the disturbed damming materials and the drainage characteristics associated with the debris along the valley.

An ice-cored moraine dam usually has a hummock dissected end moraine with smaller ponds in some cases, which show a coarse texture in satellite images. The lateral moraine ridges are generally of a smooth, narrow, linear appearance and are easily identifiable on the images. The channel path along which glacial lake outburst flooding has occurred shows distinct light tone widths along the drainage channel and banks due to bank erosion and deposition in different places along the river. The loose materials transported and deposited along the streams have higher spectral reflectance compared to their surroundings and old stable river channels, which appear relatively lighter and brighter in the satellite image.

The technique of integrating remote-sensing data with GIS does help a lot with identification and monitoring of lakes and glaciers. The generated DEM combined with stereo satellite images, aerial photographs, and digitization of topographic map data can play a big role in deciding the rules for discrimination of features and land-cover types in GIS techniques and for better perspective viewing and presentations. DEM itself can be used to create various data sets of the glaciers (e.g., slope, aspect). DEM should be compatible with and of reliable quality when compared with other data sets. The satellite images or orthophotos can be draped over the DEM for interpretation or presentation.

Chapter 7

Inventory of Glaciers

7.1 Brief Description of Methods

The data used in this study include the TM and ETM+ images acquired in 1990 and 2000 respectively to compare each other and to detect glacier change, as well as 1:50,000 topographic maps published in the 1980s and the *Glacier Inventory of China-the Ganga Drainage basin and the Indus River Drainage basin* as reference.

The guide for compilation of the World Glacier Inventory suggests that the code system must be made on the subordination relation and direction of rivers progressively. The lettering and numbering should start from the mouth of the major stream and proceed clockwise round the basin. For convenience, the code in this inventory is basin name plus glacier coding. In order to be consistent with the data of glacier inventory, each glacier given a number proceeding clockwise.

The classification of glaciers is based on the morphological classification of glaciers by the World Glacier Monitoring Service (WGMS) (1989). Details of the classification are mentioned in Chapter 4.

Changes of glaciers during two periods can be extracted from these images and maps, and then analyzed using GIS techniques. The outline of glaciers in 1990 and 2000 were obtained by TM and ETM images respectively. The attributes related to elevation are obtained from topographic maps. Other attributes such as area, length of glaciers are acquired and computed in the GIS software ArcView.

The glacial area and length is measured with the help of GIS. Since the ice thickness data are not available, it is estimated from the equation developed for the Tianshan Mountains (Chaohai Liu and Liangfu Ding 1986)

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

Where H = means ice thickness (m) and F = glacier area (km^2)

The ice reserves were estimated by multiplying the mean thickness by the glacial area.

7.2 CHARACTERISTICS OF GLACIERS IN 1980

According to WGI, the test regions include 18 sub-basins show in Figure 2.4. There are 1810 glaciers altogether covering an area of 2991. 1635 km^2. Table 7.1 shows the number of glaciers and the area covered by those glaciers for each sub-basin.

Table 7.1: sub-basin of Himalaya-China region in 1990				
Sub-basin	**Glacier Number**	**Number Percent (%)**	**Area of glacier (km^2)**	**Area percent (%)**
Pumqu_A	36	2.28	243.1885	8.37
Pumqu_B	40	2.53	102.4320	3.52
Pumqu_C	193	12.23	344.3628	11.85
Pumqu_D	116	7.35	263.3054	9.06
Pumqu_E	14	0.89	38.6972	1.33
Pumqu_F	7	0.44	0.9724	0.03
Pumqu_G	162	10.27	287.1082	9.88
Pumqu_H	70	4.44	59.3169	2.04
Pumqu_I	78	4.94	86.0711	2.96
Poiqu	127	8.05	236.1718	8.13
Rongxer_A	26	1.65	10.3303	0.36
Rongxer_B	76	4.82	103.7000	3.57
Rongxer_C	103	6.53	197.3909	6.79
Jilongcangbu	180	11.41	423.7224	14.58
Zangbuqin	64	4.06	87.9139	3.03
Daoliqu	43	2.72	59.9199	2.06
Jiazhagangge	96	6.08	141.7715	4.88
Majiacangbu	147	9.32	219.6419	7.56
TOTAL	1578	100.00	2906.017	100.00

The **Pumqu_F** sub-basin, also the smallest one, has the smallest number of glaciers and glacier area. The number of glaciers in the **Pumqu_C** and **Pumqu_G** sub-basin is 250 and 183 respectively, but **Jilongcangbu** sub-basin accounts for the largest glacier area. This is only a simple statistic, which couldn't show the mean condition about size of glaciers in each basin. Further analysis as follow:

Table 7.2 Glacier area in each sub-basin					
Sub-basin	**Glacier Number**	**Area of glacier (km^2)**	**Mean area (km^2)**	**Max Area (km^2)**	**Min Area (km^2)**
Pumqu_A	36	243.1885	6.7552	60.5083	0.1778
Pumqu_B	40	102.4320	2.5608	17.1338	0.1104
Pumqu_C	193	344.3628	1.7843	86.1799	0.0382
Pumqu_D	116	263.3054	2.2699	32.1541	0.0259
Pumqu_E	14	38.6972	2.7641	23.4610	0.1451

Pumqu_F	7	0.9724	0.1389	0.3375	0.0568
Pumqu_G	162	287.1082	1.7723	32.8945	0.0180
Pumqu_H	70	59.3169	0.8474	7.2440	0.0242
Pumqu_I	78	86.0711	1.1035	10.7226	0.0305
Poiqu	127	236.1718	1.8596	45.1759	0.0234
Rongxer_A	26	10.3303	0.3973	2.1227	0.0318
Rongxer_B	76	103.7000	1.3645	47.1648	0.0454
Rongxer_C	103	197.3909	1.9164	25.9852	0.0461
Jilongcangbu	180	423.7224	2.3540	36.5969	0.0224
Zangbuqin	64	87.9139	1.3737	10.6184	0.1226
Daoliqu	43	59.9199	1.3935	5.1934	0.0666
Jiazhagangge	96	141.7715	1.4768	16.8426	0.0492
Majiacangbu	147	219.6419	1.4942	16.6546	0.0321
TOTAL	1578	2906.017	1.8416	86.1799	0.0180

Glaciers in the **Pumqu_F** sub-basin are very small, about 0.9724 km^2 on average, while **Jilongcangbu** has the largest glacier area.

Table 7.3: Glacier characters classified by different area classes in 1990

Glacier Size (km^2)	Number		Area (km^2)	
	Number	%	Total	%
0.0-0.1	105	6.65	6.9032	0.24
0.1-0.5	592	37.52	165.4776	5.69
0.5-1	346	21.93	248.5244	8.55
1-5	426	27.00	900.7546	31.00
5-10	63	3.99	465.1164	16.01
10-20	22	1.39	300.5509	10.34
>20	24	1.52	818.69	28.17
Total	1578	100.00	2906.017	100.00

Table 7.3 depicts the share of glacier number within different area-size classes compared to the total number of the glaciers, the share of glacier area within different area classes compared to the total glacierized area respectively. As is well known, the general characteristics of Himalayas-type glacierization are that most glaciers are small and cover a small area. For example, the numerous small glaciers with an area of less than 1km^2 cover only about 14.48% of the total glacier area.

7.3 CHARACTERISTICS OF THE GLACIERS IN 2000-2001

The ETM images acquired in 2000 were co-registered with the topographical maps and the TM image in the image processing software (ENVI). Ground control points (GCP) were selected and easily identified on both topographical maps and the RS image. By selecting enough ground control points, the root mean square error (RMS) of the co-registration was limited to 1 pixel. But in the region with large altitude difference, the error can reach 2 pixels. In order to detect the change of glaciers during 10 years more easily, glacier outline were digitized form the image.

Within the Himalaya-China region, there are 1578 glaciers altogether covering an area of 2864.33 km^2.

The glacier distribution in each sub-basin is showed in the Table 7.4.

Table 7.4: sub-basin of Himalaya-China region in 2000

Sub-basin	Glacier Number	Number Percent (%)	Area of glacier (km^2)	Area percent (%)
Pumqu_A	36	2.28	246.9034	8.62
Pumqu_B	40	2.53	103.6190	3.62
Pumqu_C	193	12.23	338.5377	11.82
Pumqu_D	116	7.35	258.0980	9.01
Pumqu_E	14	0.89	37.3181	1.30
Pumqu_F	7	0.44	0.9724	0.03
Pumqu_G	162	10.27	276.0350	9.64
Pumqu_H	70	4.44	59.3288	2.07
Pumqu_I	78	4.94	87.3469	3.05
Poiqu	127	8.05	230.5173	8.05
Rongxer_A	26	1.65	9.2299	0.32
Rongxer_B	76	4.82	100.3050	3.50
Rongxer_C	103	6.53	191.6880	6.69
Jilongcangbu	180	11.41	418.6145	14.61
Zangbuqin	64	4.06	85.7492	2.99
Daoliqu	43	2.72	60.6043	2.12
Jiazhagangge	96	6.08	143.2984	5.00
Majiacangbu	147	9.32	216.1639	7.55
TOTAL	1578	100	2864.33	100

7.4 CHANGE ANALYSIS OF GLACIERS

By comparing the data of different periods, we analyzed the activity of glaciers. The total trend is that the glaciers are retreating, which resulted from a combination of natural climatic evolution and reinforced by anthropogenic greenhouse gas. With the retreat of glaciers, rapid melting of glacier ice and snow can result in the rise of glacier lake level, which then becomes greatly vulnerable to GLOF. So, the research of glacier change is very important for human safety and economy.

Table 7.5 The glacier change of each sub-basin						
Sub-basin	**Glacier Number**			**Area of glacier (km^2)**		
	1990	**2000**	**Change**	**1990**	**2000**	**Change**
Pumqu_A	36	36	0	243.1885	246.9034	1.53
Pumqu_B	40	40	0	102.4320	103.6190	1.16
Pumqu_C	193	193	0	344.3628	338.5377	-1.69
Pumqu_D	116	116	0	263.3054	258.0980	-1.98
Pumqu_E	14	14	0	38.6972	37.3181	-3.56
Pumqu_F	7	7	0	0.9724	0.9724	0.00
Pumqu_G	162	162	0	287.1082	276.0350	-3.86
Pumqu_H	70	70	0	59.3169	59.3288	0.02
Pumqu_I	78	78	0	86.0711	87.3469	1.48
Poiqu	127	127	0	236.1718	230.5173	-2.39
Rongxer_A	26	26	0	10.3303	9.2299	-10.65
Rongxer_B	76	76	0	103.7000	100.3050	-3.27
Rongxer_C	103	103	0	197.3909	191.6880	-2.89
Jilongcangbu	180	180	0	423.7224	418.6145	-1.21
Zangbuqin	64	64	0	87.9139	85.7492	-2.46
Daoliqu	43	43	0	59.9199	60.6043	1.14
Jiazhagangge	96	96	0	141.7715	143.2984	1.08
Majiacangbu	147	147	0	219.6419	216.1639	-1.58
TOTAL	1578	1578	0	2906.017	2864.33	-1.43

NOTE: The percentage of number (area, volume) change is the total number (area, volume) change divided by the number (area, volume) at the 1990 before such changes occurred.

These latest decreases in area were 1.43% during last 10 years. Glacier changes from the 1990 to 2000 in the eight sub-basins are given in Table 7.5.

The percentage of area change for different periods were calculated as the ratio of the total decrease in area to the total area in the 1990 before area changes occurred. For example, the percentage of area change from the 1990 to 2000 are taken as $(S_{1990} - S_{2000})/S_{1990}$.

During the 1990, the total area of all 1578 measured glaciers was 2906.017 km^2, which is (seen in Table 7.5) 41.687 km^2 more than those in 2000; thus the glacier area decreased by 1.43% from the 1990 to 2000. The decrease was the greatest (-10.65%) in the **Rongxer_A** sub-basin, and second largest (-3.56%) in the **Pumqu_E** sub-basin. There are very less change in the other sub-basin.

Chapter 8

Inventory of Glacial Lakes

8.1 BRIEF DESCRIPTION OF GLACIAL LAKE INVENTORY

The inventory of glacial lakes is based on topographic maps and satellite images. There are 148 sheets topographic maps with a scale of 1:50,000 in total, which were published before 1987. The 17 scenes TM images had been used to obtain the changes of glacial lakes, while several decades ASTER images as supplement information when TM images are impacted by snow cover or clouds.

8.2 GLACIAL LAKES—THEIR NUMBERING, TYPE AND CHARACTERISTICS

A glacial lake is defined as a water mass existing in a sufficient amount and extending with a free surface in, under, beside and/or in front of a glacier and originated by glacier activities and/or retreating processes of a glacier.

The numbering of the lakes started from the mouth of the major stream and proceeded clockwise round the basin.

For the inventory of glacial lakes, it is obvious to note that the lakes associated with perennial snow and ice originate from glaciers. But the isolated lakes found in the mountains and valleys far away from the glaciers may not have a glacial origin. Due to the faster rate of ice and snow melting, possibly caused by global warming noticed during the last half of the twentieth century, accumulation of water in these lakes has been increasing rapidly. The isolated lakes above 3,500 masl are considered to be the remnants of the glacial lakes left due to the retreat of the glaciers.

The lakes are classified into erosion lakes, valley trough lakes, cirque lakes, blocked lakes, moraine-dammed lakes (lateral and end moraine-dammed lakes), and supraglacial lakes.

Erosion lakes

Glacial erosion lakes are the water bodies formed in a depression after the glacier has retreated. They may be cirque type and trough valley type lakes and are stable lakes.

Supraglacial lakes

The supraglacial lakes develop within the ice mass away from the moraine with dimensions of from 50 to 100m. These lakes may develop in any position of the glacier but the extension of the lake is less than half the diameter of the valley glacier. Shifting, merging, and draining of the lakes characterise the supraglacial lakes. The merging of lakes results in expansion of the lake area and storage of a huge volume of water with a high potential energy. The tendency of a glacial lake towards merging and expanding indicates the danger level of the GLOF.

Moraine-dammed lakes

A typical example of a moraine-dammed lake is one formed on the tongue of the Cuolangma Glacier in the Pumqu basin (Figure 8.1). In the retreating process of a glacier, glacier ice tends to melt in the lowest part of the glacier surrounded by lateral and end moraines. As a result, many supraglacial ponds are formed on the glacier tongue. These ponds sometimes enlarge to become a large lake by interconnecting with each other and have a tendency to deepen further. A moraine-dammed lake is thus born. 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 the flow is minimum.

Figure 8.1: A typical example of a moraine-dammed lake is one formed on the tongue of the Cuolangma Glacier in the Pumqu basin (ASTER satellite image of 13 October 2001)

There are two kinds of moraine: an ice-cored moraine and an ice-free moraine. Before the ice body of the glacier completely melts away, glacier ice exists in the moraine and beneath the lake bottom. The ice bodies cored in the moraine and beneath the lake are sometimes called **dead ice** or **fossil ice**. As glacier ice continues to melt, the lake becomes deeper and wider. Finally when ice contained in the moraines and beneath the lake completely melts away, the container of lake water consists of only the bedrock and the moraines.

Blocking lakes

Blocking lakes formed through glacier and other factors, including the main glacier blocking the branch valley, the glacier branch blocking the main valley, and the lakes through snow avalanche, collapse and debris flow blockade.

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. The typical ice core-dammed lakes are shown in Figure 8.2. Three lakes are seen on the right bank of the debris covered glacier tongue of the Ngozumpa Glacier in the Dudh Koshi Basin, which is one of the largest glaciers in the Nepal Himalayas and flows from top to bottom in the figure. The lakes were still frozen and covered by snow when the image was captured. Since the glaciers in the Nepal Himalayas produce relatively rich debris, thick lateral moraines are deposited on both sides of the glacier tongue. 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.

A glacial lake is formed and maintained only up to a certain stage of glacier fluctuation. If one follows 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 or when debris fills the lakes completely or the mother glacier advances again to lower altitudes beyond the moraine-dam position. Such glacial lakes are essentially ephemeral and are not stable from the point of view of the life of glaciers.

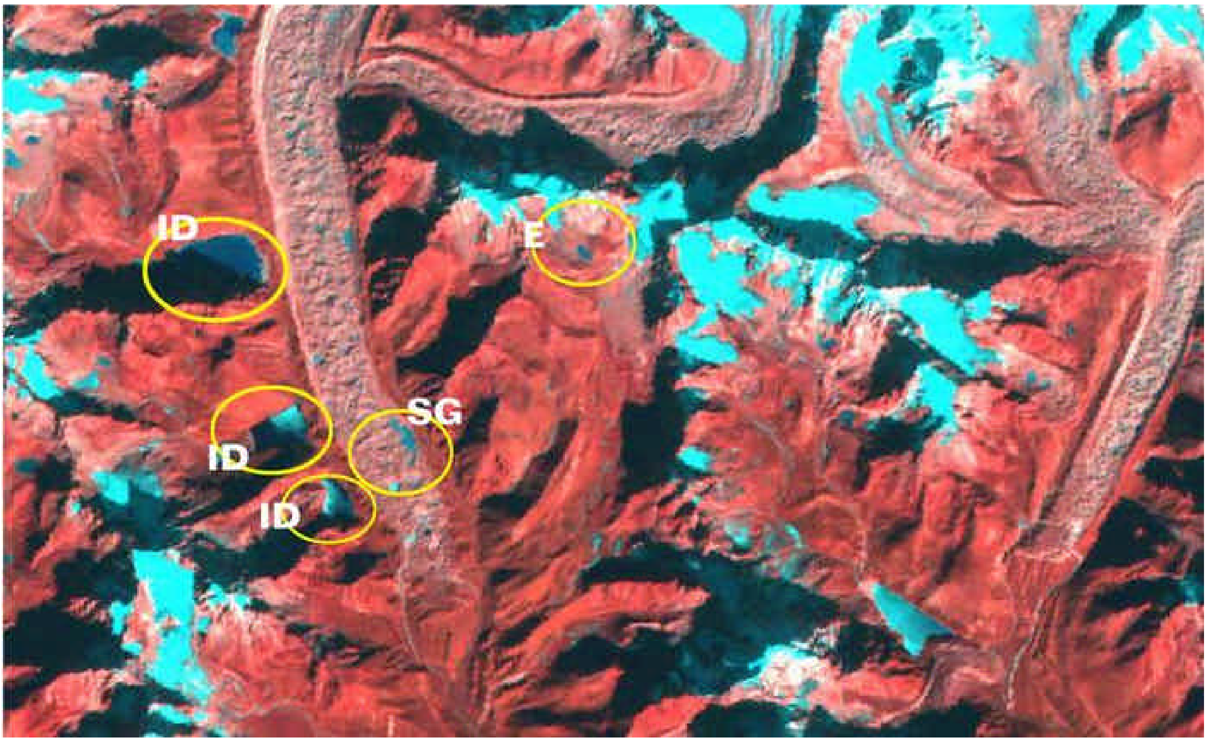


Figure 8.2: The lakes labelled ID, SG, and E represent ice core-dammed, supraglacial, and erosion lakes respectively around the Ngozumpa Glacier, one of the largest glaciers in the Nepal Himalayas (LANDSAT TM satellite image of 17 December 1991)

In generally, only moraine-dammed lakes pose a threat in the Pumqu Basin. The description hereafter is, thus, mainly concentrated on moraine-dammed lakes and associated outburst floods.

8.3 GLACIAL LAKES OF HIMALAYA-CHINA REGION

There are 824 lakes in the Himalayan-China Regions covering an area of around 85.191 sq. km., including erosion lakes, cirque lakes, end moraine dammed lakes, valley trough 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 originating glaciers or connects directly to the originating glaciers. Because water level and stability of the dam are directly affected by the glacier variation, and the Little ice Age moraine ridges developed rather recently, the moraine materials have not cemented hard enough to become a rock. The dam is very easy to burst and form an extraordinary serious flood or debris flow (Table 8.1).

Table 8.1: Distribution of lakes in the sub-basins of the Himalayan-China Region

Basin Name	Number of Lakes	Area (km^2)	Mean area per lake (km^2)
Jiazhagangge	14	0.515	0.037
Daoliqu	7	0.377	0.054
Majiacangbu	69	4.734	0.069
Jilongcangbu	72	3.317	0.046
Poiqu	91	15.661	0.172
Pumqu	383	52.008	0.136
Rongxer	183	8.395	0.046
Zangbuqin	5	0.183	0.037
Total	824	85.1914	0.1034

Jiazhagangge basin

The **Jiazhagangge** basin is the one of westernmost branch of the Himalayan-China basin. There are 10 moraine-dammed lakes in total, and only one lake is dangerous. And the erosion lakes and valley lakes are not potentially dangerous as they are isolated and not associated with the hanging glaciers. (Table 8.2)

Table 8.2: Types of lakes in the Jiazhagangge basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake (m^2)
Erosion	3	21.43	15854.89	9.24	28598.38
Moraine dammed	10	71.43	43634.61	84.74	68921.52
Valley	1	7.14	31026.18	6.02	31026.18

Daoliqu basin

Though there are only 7 lakes in the **Daoliqu** basin, all of them are moraine-dammed lakes but one erosion lake. After analysis of these lakes change in two different periods, we found no lakes belong to the potentially danger lakes. (Table 8.3)

Table 8.3: Types of lakes in the Daoliqu basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake

					(m²)
Erosion	1	14.29	50844.72	13.50	50844.72
Moraine dammed	6	85.71	325659.73	86.50	93291.24

Majiacangbu basin

The **Majiacangbu** basin is one of the most dangerous basins, and these dangerous lakes locate the eastern of basin. In total, there are 11 danger lakes in this basin (Table 8.4)

Table 8.4: Types of lakes in the Majiacangbu basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake (m^2)
Cirque	5	7.25	604711.46	12.77	285980.70
Erosion	26	37.68	1363042.92	28.79	624406.40
Moraine dammed	24	34.78	2497764.88	52.77	451944.60
Supraglacial	9	13.04	84393.36	1.78	22738.89
Valley	5	7.25	183824.49	3.88	64860.35

Jilongcangbu basin

In the **Jilongcangbu** basin, the number of glacial lakes is large, and it is one of dangerous sub-basins. (Table 8.5)

Table 8.5: Types of lakes in the Jilongcangbu basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake (m^2)
Cirque	4	5.56	101429.15	3.06	50564.51
Erosion	19	26.39	495696.32	14.94	88642.99
Moraine dammed	31	43.06	2111456.10	63.65	424676.27
Supraglacial	6	8.33	69247.21	2.09	19788.16
Valley	12	16.67	539655.68	16.27	162816.11

Poiqu basin

The **Poiqu** basin also is one of dangerous sub-basins, and there are 91 lakes in total. In final, 9 lakes are identified as potentially danger lakes. (Table 8.6)

Table 8.6: Types of lakes in the Poiqu basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake (m^2)
Blacking	1	1.10	2295810.38	14.66	2295810.38
Erosion	47	51.65	1618276.07	10.33	312973.43
Moraine dammed	28	30.77	10354219.70	66.11	3373971.19
Supraglacial	3	3.30	87897.50	0.56	37236.95
Valley	12	13.19	1305151.74	8.33	498951.43

Pumqu basin

The **Pumqu** basin is the largest basin in this research region, and there are 383 lakes distributed in 9 sub-basins. Pumqu basin also is the dangerous basin, 38 lakes are identified as potentially danger lakes. (Table 8.7)

Table 8.7: Distribution of lakes in the sub-basins of the Pumqu basin

Sub-asin Name	Number of Lakes	Area (km^2)	Mean area per lake (km^2)
Ganmazangbo	56	3.180	0.057
Kadapu	51	6.258	0.123
Zhagarqu	19	1.208	0.064
Zongbuxan	30	7.667	0.256
Moinqu	7	5.290	0.756
Loloqu	56	5.491	0.098
Yarozangbo	43	9.921	0.231
Bailungpu	63	7.374	0.117
Natangqu	58	5.619	0.097
Total	383	52.008	0.136

Ganmazangbo sub-basin

Table 8.8: Types of lakes in the Ganmazangbo sub-basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake (m^2)
Erosion	52	92.86	2401414.23	75.50	261329.11
Moraine dammed	1	1.79	323329.85	10.17	323329.85
Valley	3	5.36	455726.82	14.33	391663.40

Kadapu sub-basin

Table 8.9: Types of lakes in the Kadapu sub-basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake (m^2)
Erosion	21	41.18	1143671.28	18.28	230963.47
Moraine dammed	7	13.73	1276974.35	20.41	607776.41
Valley	23	45.10	3837176.47	61.32	1033599.03

Zhagarqu Sub-basin

Table 8.10: Types of lakes in the Zhagarqu sub-basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake

					(m^2)
Blocking	1	5.26	572276.72	47.38	572276.72
Erosion	6	31.58	216553.90	17.93	109759.78
Moraine dammed	3	15.79	195688.28	16.20	150840.08
Supraglacial	9	47.37	223350.09	18.49	109779.25

Zongbuxan sub-basin

Table 8.11: Types of lakes in the Zongbuxan sub-basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake (m^2)
Erosion	9	30.00	446699.29	5.83	269548.80
Moraine dammed	19	63.33	7091489.86	92.50	4135052.36
Supraglacial	2	6.67	128660.57	1.68	107454.62

Moinqu sub-basin

Table 8.12: Types of lakes in the Moinqu sub-basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake (m^2)
Moraine dammed	2	28.57	227102.45	4.29	213555.89
Valley	5	71.43	5063375.24	95.71	2783950.82

Loloqu sub-basin

Table 8.13: Types of lakes in the Loloqu sub-basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake (m^2)
Cirque	3	5.36	767022.59	13.97	543142.21
Erosion	11	19.64	682529.60	12.43	336315.02
Valley	42	75.00	4041626.31	73.60	390059.37

Yarozangbo sub-basin

Table 8.14: Types of lakes in the Yarozangbo sub-basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake

					(m²)
Erosion	7	16.28	301438.26	3.04	146860.56
Moraine dammed	32	74.42	8504304.04	85.72	1112609.70
Valley	4	9.30	1114989.97	11.24	808750.34

Bailungpu sub-basin

Table 8.15: Types of lakes in the Bailungpu sub-basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake (m^2)
Blocking	1	1.59	1326268.61	17.98	1326268.61
Erosion	36	57.14	1693892.14	22.97	209914.30
Moraine dammed	19	30.16	3641594.79	49.38	846200.23
Valley	7	11.11	712694.75	9.66	341585.38

Natangqu sub-basin

Table 8.16: Types of lakes in the Natangqu sub-basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake (m^2)
Erosion	31	53.45	880510.90	15.67	111650.47
Moraine dammed	20	34.48	2956668.95	52.62	901023.23
Supraglacial	1	1.72	55962.50	1.00	55962.50
Valley	6	10.34	1725403.30	30.71	1458918.72

Rongxer basin

The **Rongxer** basin is also one of dangerous basins, and there are 183 lakes in total. (Table 8.17) In final, 16 lakes are identified as potentially danger lakes.

Table 8.17: Distribution of lakes in the sub-basins of the Rongxer basin

Sub-asin Name	Number of Lakes	Area (km^2)	Mean area per lake (km^2)
Rongxer Qu_A	24	0.2150	0.0090
Rongxer Qu_B	74	2.2973	0.0310
Rongxer Qu_C	85	5.8824	0.0692
Total	183	8.3947	0.0459

Rongxer Qu_A sub-basin

Table 8.18: Types of lakes in the Rongxer Qu_A sub-basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake (m^2)
Erosion	20	83.33	180480.17	83.94	25944.61

Moraine dammed	1	4.17	16846.79	7.84	16846.79
Valley	3	12.50	17691.55	8.23	7755.70

Rongxerqu Qu_B sub-basin

Table 8.19: Types of lakes in the Rongxer Qu_B sub-basin

Type	Number	Number (%)	Area (m^2)	Area (%)	Area of largest lake (m^2)
Erosion	35	47.30	746737.47	32.50	76896.94
Moraine dammed	20	27.03	1354046.46	58.94	260082.20
Supraglacial	18	24.32	159066.66	6.92	49558.95
Valley	1	1.35	37462.03	1.63	37462.03

Rongxer Qu_C sub-basin

Table 8.20: Types of lakes in the Rongxer Qu_C sub-basin					
Type	**Number**	**Number (%)**	**Area (m^2)**	**Area (%)**	**Area of largest lake (m^2)**
Blocking	1	1.18	193636.58	3.29	193636.58
Erosion	53	62.35	1448031.64	24.62	175904.69
Moraine dammed	16	18.82	4057936.80	68.98	793293.47
Supraglacial	15	17.65	182774.72	3.11	40657.39

Zangbuqin basin

The **Zangbuqin** basin is a small basin, and there are only 5 lakes. There are no potentially danger lakes. (Table 8.21)

Table 8.21: Types of lakes in the Zangbuqin basin					
Type	**Number**	**Number (%)**	**Area (m^2)**	**Area (%)**	**Area of largest lake (m^2)**
Erosion	1	20.00	43256.73	23.58	43256.73
Moraine dammed	4	80.00	140155.51	76.42	94743.19

Chapter 9

Glacial Lake Outburst Floods and Damage in the Country

9.1 INTRODUCTION

Periodic or occasional release of large amounts of stored water in a catastrophic outburst flood is widely referred to as a **jokulhlaup** (Iceland), a **debacle** (French), an **aluvión** (South America), or a **Glacial Lake Outburst Flood** (GLOF) (Himalaya). A **jokulhlaup** is an outburst which may be associated with volcanic activity, a **debacle** is an outburst but from a proglacial lake, an **aluvión** is a catastrophic flood of liquid mud, irrespective of its cause, generally transporting large boulders, and a GLOF is a catastrophic discharge of water under pressure from a glacier. GLOF events are severe geomorphological hazards and their floodwaters can wreak havoc on all human structures located on their path. Much of the damage created during GLOF events is associated with the large amounts of debris that accompany the floodwaters. Damage to settlements and farmland can take place at very great distances from the outburst source, for example in Pakistan; damage occurred 1,300 km from the outburst source (WECS 1987b).

9.2 CAUSES OF LAKE CREATION

Global warming

There is growing concern that human activities may change the climate of the globe. Past and continuing emissions of carbon dioxide (CO_2) and other gases will cause the temperature of the Earth's surface to increase—this is popularly termed 'global warming' or the 'greenhouse effect'. The 'greenhouse effect' gives an extra temperature rise.

Glacier retreat

An important factor in the formation of glacial lakes is the rising global temperature ('greenhouse effect'), which causes glacial retreat in many mountain regions.

During the so-called 'Little Ice Age' (AD 1550–1850), many glaciers were longer than today. Moraines formed in front of the glaciers at that time nowadays block the lakes. Glaciation and interglaciation are natural processes that have occurred several times during the last 10,000 years.

As a general rule, it can be said that glaciers in the Himalayas have retreated about 1 km since the Little Ice Age, a situation that provides a large space for retaining melt water, leading to the formation of moraine-dammed lakes (LIGG/WECS/NEA 1988).

Röthlisberger and Geyh (1985) conclude in their study on 'glacier variations in Himalaya and Karakorum' that a rapid retreat of nearly all glaciers with small oscillation was found in the period from 1860/1900–1980.

Causes of glacial lake water level rise

The causes of rise in water level in the glacial lake dammed by moraines that endanger the lake to reach breaching point are given below.

- Rapid change in climatic conditions that increase solar radiation causing rapid melting of glacier ice and snow with or without the retreat of the glacier.
- Intensive precipitation events
- Decrease in sufficient seepage across the moraine to balance the inflow because of sedimentation of silt from the glacier runoff, enhanced by the dust flow into the lake.
- Blocking of ice conduits by sedimentation or by enhanced plastic ice flow in the case of a glacial advance.
- Thick layer of glacial ice (dead ice) weighed down by sediment below the lake bottom which stops subsurface infiltration or seepage from the lake bottom.
- Shrinking of the glacier tongue higher up, causing melt water that previously left the glacier somewhere outside the moraine, where it may have continued underground through talus, not to follow the path of the glacier.
- Blocking of an outlet by an advancing tributary glacier.
- Landslide at the inner part of the moraine wall, or from slopes above the lake level
- Melting of ice from an ice-core moraine wall.
- Melting of ice due to subterranean thermal activities (volcanogenic, tectonic).
- Inter-basin sub-surface flow of water from one lake to another due to height difference and availability of flow path.

9.3 BURSTING MECHANISMS

Different triggering mechanisms of GLOF events depend on the nature of the damming materials, the position of the lake, the volume of the water, the nature and position of the associated mother glacier, physical and topographical conditions, and other physical conditions of the surroundings.

Mechanism of ice core-dammed lake failure

Ice-core dammed (glacier-dammed) lakes drain mainly in two ways.

- through or underneath the ice
- over the ice

Initiation of opening within or under the ice dam (glacier) occurs in six ways.

- Flotation of the ice dam (a lake can only be drained sub-glacially if it can lift the damming ice barrier sufficiently for the water to find its way underneath).
- Pressure deformation (plastic yielding of the ice dam due to a hydrostatic pressure difference between the lake water and the adjacent less dense ice of the dam; outward progression of cracks or crevasses under shear stress due to a combination of glacier flow and high hydrostatic pressure).
- Melting of a tunnel through or under the ice
- Drainage associated with tectonic activity
- Water overflowing the ice dam generally along the lower margin
- Sub-glacial melting by volcanic heat

The bursting mechanism for ice core-dammed lakes can be highly complex and involve most or some of the above-stated hypothesis. Marcus (1960) considered ice core-dammed bursting as a set of interdependent processes rather than one hypothesis.

A landslide adjacent to the lake and/or subsequent partial abrasion on ice may lead to overtopping as the water flows over, the glacier retreats, and the lake fills rapidly, which may subsequently result in the draining of ice core moraine-dammed lakes.

Mechanisms of moraine-dammed lake failure

Moraine-dammed lakes are generally drained by rapid incision of the sediment barrier by outpouring waters. Once incision begins, the hustling water flowing through the outlet can accelerate erosion and enlargement of the outlet, setting off a catastrophic positive feedback process resulting in the rapid release of huge amounts of sediment-laden water (Figure 9.1). The onset of rapid incision of the barrier can be triggered by waves generated by glacier calving or ice avalanching, or by an increase in water level associated with glacial advance (examples include an ice avalanche from Langmoche Glacier on 4 August 1985 and another on 3 September 1998 from Sabai Glacier).

Dam failure can occur for the following reasons:

- melting ice core within the moraine dam,
- rock and/or ice avalanche into a dammed lake,
- settlement and/or piping within the moraine dam,
- sub-glacial drainage, and
- engineering works.

Melting ice-core

The melting of impervious ice core within a moraine dam may result in the lowering of the effective height of the dam, thus allowing lake water to drain over the residual ice core. As the discharge increases with the melting of the ice core, greater amounts of water filter through the moraine, carrying fine materials. Eventually, the resulting regressive erosion of the moraine dam leads to its ultimate failure.

Overtopping by displacement waves

Lake water is displaced by the sudden influx of rock and/or ice avalanche debris. The resultant waves overtop the freeboard of the dam causing regressive and eventual failure.

Settlement and/or piping

Earthquake shocks can cause settlement of the moraine. This reduces the dam freeboard to a point that the lake water drains over the moraine and causes regressive erosion and eventual failure.

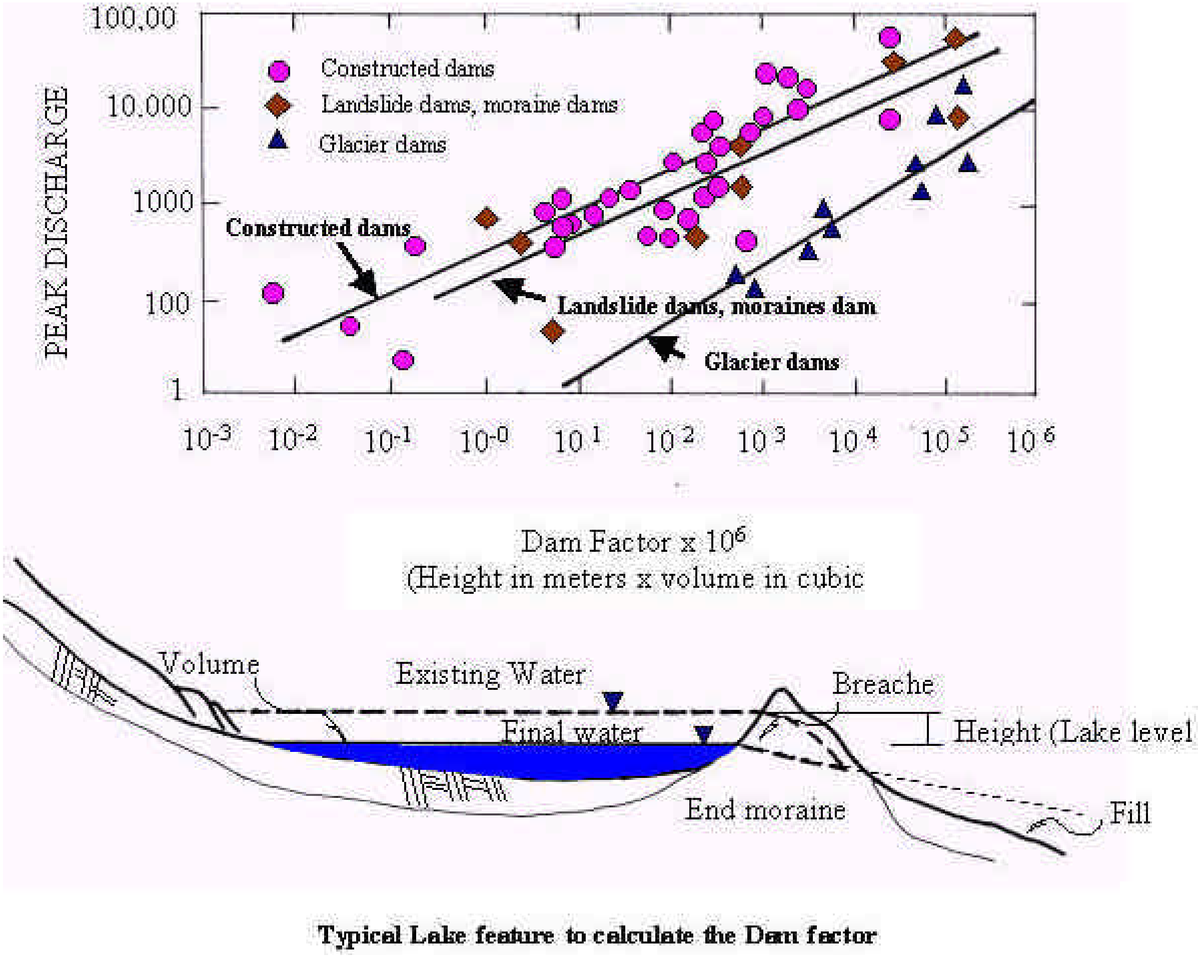


Figure 9.1: Peak discharge from breached moraine-dammed lakes can be estimated from an empirical relationship developed by Costa (1985)

Sub-glacial drainage

A receding glacier with a terminus grounded within a proglacial lake can have its volume reduced without its ice front receding up-valley. When the volume of melt water within the lake increases to a point that the formerly grounded glacier floats, an instantaneous sub-glacial drainage occurs. Such drainage can destroy any moraine dam, allowing the lake to discharge until the glacier loses its buoyancy and grounds again.

Engineering works

One of the main difficulties in changing water levels or dam structures artificially is that this can unintentionally trigger a catastrophic discharge event. For example, in Peru in 1953, during the artificial lowering of the water level, an earth slide caused 12m high displacement waves, which poured into a trench, excavated as part of the engineering works and almost led to the total failure of the moraine dam.

9.4 SURGE PROPAGATION

As GLOFs pose severe threats to humans and man-made structures, it is important to make accurate estimates of the likely magnitude of future floods. Several methods have been devised to predict peak discharges, which are the most erosive and destructive phases of floods. The surge propagation hydrograph depends upon the type of GLOF event, i.e. from moraine-dammed lake or from ice-dammed lake (Figure 9.2). The duration of a surge wave from an ice-dammed lake may last for days to even weeks, while from a moraine-dammed lake the duration is shorter, minutes to hours. The peak discharge from the moraine-dammed lake is usually higher than those from ice-dammed lakes.

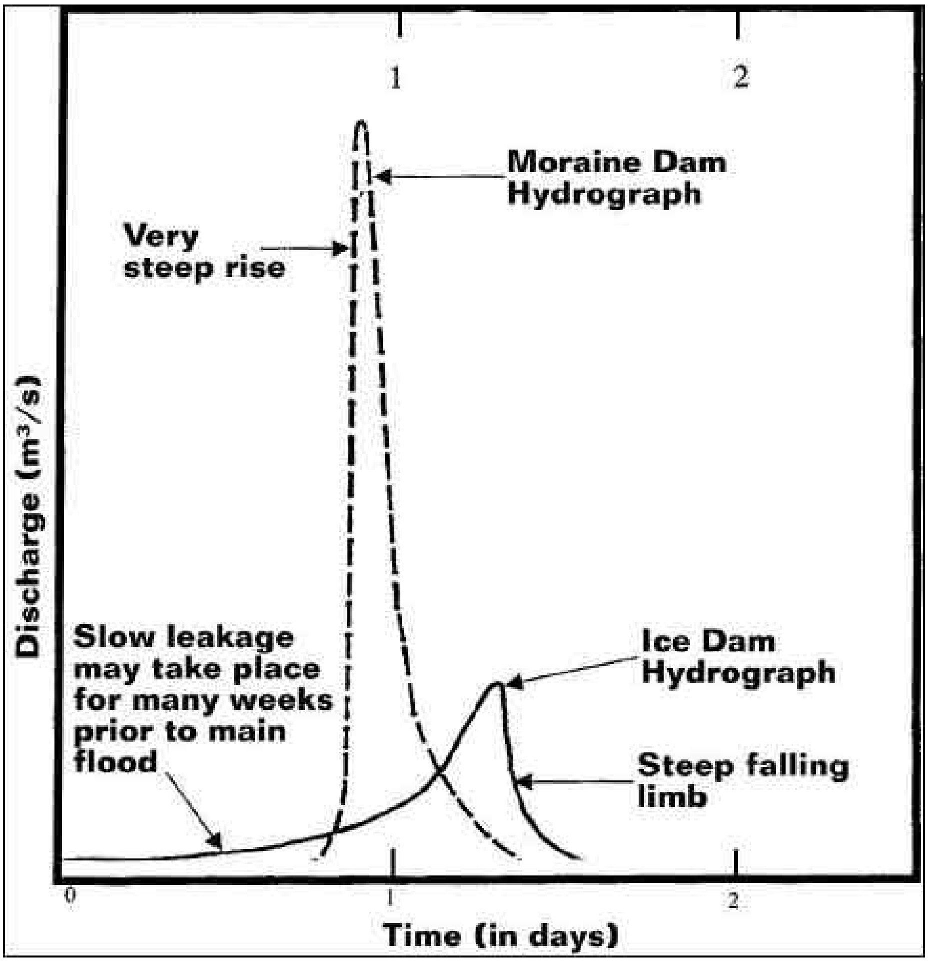


Figure 9.2: Difference in release hydrograph between moraine- and ice-dammed lakes (WECS 1987A)

The following methods have been proposed for estimation of peak discharges.

1) Clague and Mathews formula

Clague and Mathews (1973) were the first to show the relationship between the volume of water released from ice-dammed lakes and peak flood discharges.

$Q_{max} = 75(V_0 * 10^{-6})^{0.67}$

where

Q_{max} = peak flood discharge ($m^3 s^{-1}$)

V_0 = total volume of water drained out from lake (m^3)

The above relationship was later modified by Costa (1988) as the peak discharge yielded from the equation was higher than that measured for Flood Lake in British Columbia that occurred in August 1979:

$Q_{max} = 113(V_0 * 10^{-6})^{0.64}$

Later Desloges et al. (1989) proposed:

$Q_{max} = 17 V_0 * 19(0^{-6})^{0.64}$

This method of discharge prediction is not based on any physical mechanism, but seems to give reasonable results.

2) Mean versus maximum discharge method

If the volume of water released by a flood and the flood duration are known, the mean and peak discharges can be calculated. Generally the flood duration will not be known in advance. Hence, this method cannot be used to determine the magnitude of future floods. Observations of several outburst floods in North America, Iceland, and Scandinavia have shown that peak discharges are between two to six times higher than the mean discharge for the whole event.

3) Slope area method

This method is based on measured physical parameters such as dimensions and slope of channel during peak flood conditions from direct observations or geomorphological evidence.

$Q_{max} = vA$

The peak velocity is calculated by the Gauckler–Manning formula (Williams 1988)

$v = r^{0.67} S^{0.50}/n$

where

v = peak velocity

S = bed slope for a 100m channel reach

n = Manning's roughness coefficient

r = hydraulic radius of the channel

$r = A/p$

where

A = cross-sectional area of the channel

p = perimeter of the channel under water

For sediment floored channels, bed roughness is mainly a function of bed material, particle size, and bed form or shape and can be estimated from:

$n = 0.038D^{0.167}$

where,

D = average intermediate axis of the largest particles on the channel floor.

Desloges et al. (1989) compared the results from all the three methods for a jokulhlaup from the ice-dammed Ape Lake, British Columbia. All the methods gave comparable results.

- The Clague and Mathews method gave a calculated peak discharge of 1,680 ± 380 m3 s-1.
- The mean versus maximum discharge method gave 1,080–3,240 m3 s–1.
- The slope area method gave 1,534 and 1,155 m3 s–1 at a distance of 1 and 12 km from the outlet respectively.

These general relationships are useful for determining the order of magnitude of initial release that may propagate down the system. However, to predict the magnitude of future floods, the first method should be applied, because volume of lake water can be estimated in advance.

Attenuation of a peak discharge of 15,000–20,000m^3 s^{-1} has been reported for the Sun Koshi River in Tibet within a distance of 50 km (XuDaoming 1985) (Figure 9.11). The propagation of surge waves can be numerically modeled using the dam-break flood-forecasting model.

9.5 SEDIMENT PROCESSES DURING A GLACIAL LAKE OUTBURST FLOOD

During a GLOF, the flow velocity and discharge are exceptionally high and it becomes practically impossible to carry out any measurement. Field observations after a GLOF event have shown a much higher sediment concentration of rivers than before the GLOF event (Electrowatt Engineering Service Ltd 1982; WECS 1995a). WECS (1995a) calculated the volume of scoured sediment as $22.5*10^4$ m^3 after the Chubung GLOF in 1991. A high concentration of 350,000 mg^{-1} during a GLOF in the Indus River at Darband in 1962 is reported by Hewitt (1985). Hypothetical illustrations showing discharge and variation in sediment concentration (WECS 1987a) are shown in Figure 9.3.

The total sediment load is generally accepted as the wash load, which moves through a river system and finally deposits in deltas. In Nepal, no measurements have been taken of total sediment during GLOF events, however, rough estimates of total load during torrents can be made assuming a high sediment concentration (WECS 1987b). During a GLOF event, stones the size of small houses can be easily moved (WECS 1987b). The relationship between flow velocity and particle diameter can also be used to calculate the size of boulders that can be moved during such events.

9.6 SOCIOECONOMIC EFFECTS OF GLACIAL LAKE OUTBURST FLOODS

The impact of a GLOF event downstream is quite extensive in terms of damage to roads, bridges, trekking trials, villages, and agricultural lands as well as the loss of human lives and other infrastructures. The sociological impacts can be direct when human lives are lost, or indirect when the agricultural lands are converted to debris filled lands and the village has to be shifted. The records of past GLOF events show that once every three to ten years, a GLOF has occurred in Nepal with varying degrees of socioeconomic impact. Therefore, proper hazard assessment studies must be carried out in potentially problematic basins to evaluate the likely economic loss and the most appropriate method of mitigation activities.

The 1981 GLOF from Zhangzangbo in Tibet (China) brought a lot of destruction in Tibet (China) and Nepal. It even caused severe damage to sections of the Nepal–China Highway including the Phulping and Friendship bridges in Nepal. The road was rebuilt at a cost of US $3 million. The present road level is now above the historic 1981 GLOF.

The 1985 GLOF from Dig Tsho in the Dudh Koshi Basin damaged Namche hydropower station (US $1.5 million), 14 bridges, cultivated lands etc. (Vuichard and Zimmerman 1987). The hydropower plant has been rebuilt at another site. The sociological cost of lost lives and dwellings to communities was enormous. The study shows that this glacial lake is refilling again and possibly engineering a greater risk of a GLOF occurrence in the same basin. This and many more GLOF events indicate that before any major project is undertaken in the basin, in-depth cost and benefit analyses have to be carried out for deciding on the most appropriate alternative that will enable project financiers to assess their risks from a GLOF. The assessment of tangible benefits in respect to mitigation of GLOFs is, however, difficult. Reduced damage is considered a benefit and can be quantified, but the frequency of the reduced damage is difficult to ascertain due to lack of data. One cannot simply predict the timing and occurrences of GLOFs. It is extremely difficult to simulate numerically the flood level and velocities at a particular place.

At this stage, from brief studies of GLOFs throughout the world, it appears that there are no simple direct means of estimating the recurrence of GLOFs.

9.7 BRIEF REVIEW OF GLACIAL LAKE OUTBURST FLOOD EVENTS AND DAMAGE CAUSED

The reported GLOF events are given in Table 9.1. In 1964, the Gelhaipuco GLOF was experienced along the Arun Valley. Severe damage and heavy economic losses occurred in Chinese Territory. And, the Ayaco Lake had GLOF every year from 1968 to 1970.

Table 9.1: List of GLOF events that have occurred in Pumqu basin, affecting Nepal

No.	Index	Date	River basin	Lake	Source	Cause of GLOF	Losses
1	1	21 September 1964	Arun	Gelhaipco	Natangqu sub-basin	Glacier surge	Highway and 12 trucks
2	2	1968	Arun	Ayaco	Zongboxan River	Not known	Road, bridges etc
3	2	1969	Arun	Ayaco	Zongboxan River	Not known	Not known
4	2	1970	Arun	Ayaco	Zongboxan River	Not known	Not known
5	3	27 August 1982	Arun	Jinco	Yarozangbo River	Glacier surge	Livestock, farmland

Gelhaipuco

Gelhaipuco is an end moraine-dammed lake located in the headwaters of the Gelhaipu Gully (Natangqu River Basin), east of Riwo, Dinggye County, Tibet (China). Its geographic position is latitude 27º 58' N and longitude 87º 49' E. The lake burst abruptly due to an ice avalanche at 2 pm, on 21 September 1964. According to an investigation by Chengdu Institute of Geography of the Chinese Academy of Sciences, from the middle of March to the end of September 1964, there was a large precipitation in the Natangqu River Basin, which caused the glacier of the Natangqu River to slide (LIGG/WECS/NEA 1988). Huge amounts of ice slid into the lake resulting in the generation of a shock wave and water level increase. Finally, the lake water overflowed through the moraine dam and breached the 30m steep valley through the dam.

The flood, with a huge amount of debris, damaged Chentang-Riwo Highway and 12 trucks transporting timber were washed away. The debris flow rushed down to the lower reaches of the Arun (Pumqu) River of Nepal and caused heavy economic losses. Based on flood trace marks and sediment deposits on the river-bed, it was concluded that it was a turbulent debris flow with a bulk density of about 1.45 t m^{-3}.

Before the burst, Gelhaipuco Lake was 1.4 km in length and 0.548 sq. km in area with water reserves of about 25.45 million m^3. The water level of the lake dropped by 40m after the lake burst in 1964 and released about 23.36 million m^3 of water. The slope of the exposed lake bed is 0.6% and it is 0.2 km away from the glacier margin. The present condition of the lake indicates stability. But if the glacier advances forward again, the possibility of another burst cannot be ruled out.

The LANDSAT TM and field photographs of Gelhaipuco Lake are given in Figures 9.3, 9.4, and 9.5 respectively.

Figure 9.3: LANDSAT TM of 22 September 1988 (the Gelhaipuco Glacial Lake area is shown in the circle)

Figure 9.4: The field photograph (1987) of Gelhaipuco Glacial Lake shows the lake in contact with the hanging glacier

Figure 9.5: The eroded banks of the Natangchu (tributary of the Pumqu River in Tibet [China]) after the Gelhaipuco GLOF in 1964 (photograph 1987)

A

Ayaco is located at the headwaters of the Zongboxan River in the Pumqu Basin (Tibet) on the northwestern slope of Mount Everest. The geographic position of the lake is latitude 28º 21'N and longitude 86º 29'E. According to an investigation by Chengdu Institute of Geography of the Chinese Academy of Sciences, there were three burst events recorded in mid August 1968, 1969, and 1970 (LIGG/WECS/NEA 1988). A huge fan-shaped mass of debris was deposited at the confluence of the lake drainage channel and the main river course. The estimated sediment deposit is about 4.59 million m^3. At present the lake is only 1.2 km long and 0.35 sq. km in area, which is much smaller than its size before the burst. The distance from the glacier to the lake is 0.5 km. If the glacier advances again, there is the possibility of another burst, but the intensity may not be as strong as during the period from 1968–1970. The flood damaged the highway and concrete bridges of Desha No.1 in Tibet (China). The damage on the Nepal side is unknown.

Jinco

Jinco Lake is located at the headwaters of the Yairuzangbo River of the Pumqu Basin (Tibet) and the Arun Basin in Nepal. It is an end moraine-dammed lake. The Jinco GLOF happened at 5 pm on August 27 1982 and formed a huge amount of debris flow. At 7 pm the flood peak arrived at Sar. The summer of 1982 was dry and hot. The outburst might have been the result of a strong glacier ablation that seeped melting water into the glacier bed and made it slide. The ice blocks collapsed into the lake and the generated shock wave damaged the dam, thus causing the burst.

Over 1,600 livestock were lost, about 19 hectares of cultivated field were destroyed, and the houses of eight villages were washed away. Gujing village suffered a different degree of destruction.

Zhangzangbo

At mid-night, July 11, 1981, an end moraine-dammed lake located at the headwaters of Zhangzangbo Gully burst suddenly in Poiqu basin. A breach 50 m deep and 40--60m of bottom width was formed at the Little Ice Age moraine dam. The flood formed a large alluvial fan. According to Xudaoming, the largest burst discharge was about 1600 m^3/s, which happened 23 minutes after the burst. The main flood lasted about 60 minutes and the burst water amount was estimated at 19 million m^3. Along the valley where the debris flow passed through, erosion and sedimentation can be seen; about 4 million m^3 of mixed materials joined the debris flow process. This debris flow damaged the highway between the outlet of Zhangzangbo Gully and the Sun Koshi Power Station in Nepal. It destroyed the Friendship Bridge of the China-Nepal Highway and the intake dam of Sun Koshi Hydroelectric Station, causing serious economic losses to Nepal. According to the investigation of Xudaoming et al. in 1984, before the burst, the end moraine-dammed lake was 1.7 km long and 0.643 km^2 in area; after the burst the length and area were reduced to 1.1 km and 0.265 km^2, respectively. The water reserves of the lake were also greatly reduced.

According to the investigation of 1984, there had been a burst in 1964 from that same lake, but the breach was different from that in 1981 and the scope of the debris flow, burst discharge and the damage caused, was smaller. There is a cirque-hanging glacier in Zhangzangbo Gully (Glacier No. 91 (LIGG/NEA/WECS 1988)), whose area is 2.47 km^2, length 2.2 km and it ends at the bank of the lake. From the 5th to the 10th of July, 1981, there was continuous hot weather. The increased glacier ablation produced a large amount of water seeping into the crevasse of the glacier tongue, which brought the glacier into a critical state and caused part of the glacier to slide. Huge amounts of ice collapsed into the lake which generated the shock wave that caused the dam burst.

Taraco

Taraco lake is located in the Targyailing Gully at 28º17´ N, 86 º09´ E in Poiqu basin. Now it is a moraine dammed lake, 1.0 km in length, 0.224 km^2 in area. According to local old residents descriptions, in a night of August, 1935, the lake burst abruptly. It happened during the wheat harvest season. Nearly 100 mu of wheat field at the outlet of the gully were destroyed, and several heads of yaks were lost. A large fan-shaped area of debris flow outside the Targyailing Gully was formed at that burst. Now it is a vast expanse of stone and can not be cultivated. According to the description of local old men, there was water oozing from beneath the dam before that burst. It can be concluded that the burst was probably caused by part of the dam collapsing because of seepage. There is a cirque-hanging glacier (No. 74 (LIGG/NEA/WECS 1988)) behind the lake, with an area of 2.46 km^2 and 1.5 km in length. Now the terminus of the glacier is 0.3 km away from the lake. If the glacier moves forward again, it is still possible to have another burst, but the scale and damage degree would not be as high as in 1935.

Yadong

At the boundary headwater between upper Kangma District of Yadong in Xizang (Tibet), and Sikkim there is an end moraine dammed lake named Qubixiama. Its length is 450 m, width over one hundred meters, water level 4560 masl, and the end moraine dam is 70 m higher than the riverbed. In rhe night of June 10th, 1940, the glacier behind the lake collapsed abruptly into the lake. The shock wave generated broke up the dam and induced a burst. Estimated from the water trace mark left from the burst, the discharge was as high as 3690 m^3 s, and the flow velocity 7.7 m/ s. According to the witness, the burst flood subsided half hour later. This glacier lake burst caused the water level of Xiasima (where the County is sited), Yadong, to rise to 4 5m; the street was flooded and some buildings were damaged.

Jiangzi

There is an end moraine dammed glacier lake named Sangwang at the headwaters of the Nyabgqu River at the boundary of Bhutan. Behind the lake there are two cirque – hanging glaciers. After several days of hot weather in mid July 1954, the hanging glacial tongue slided into the lake abruptly in the night of July 16. The strong shock waves generated and the huge amount of ice blocks burst the dam. Jiangzi flood as high as 4 meters surged down; a large amount of gravel carried by the flood formed deposit layers of up to 3-5 m thick on the valley plain. This sever flood and debris flow seriously damaged towns and cultivated fields.

Tanbulang debris flow of 1964

The Tangbulang Gully is a tributary in the east side of the Niyang River, 15 km long, trending in the northeast direction. The Sichuan –Xizang Highway is located at the outlet of the valley. There are eight cirque glaciers and cirque – hanging glaciers at the headwaters of the valley; below the glacier there are over ten small moraine – dammed lakes. Among these lakes the largest is named Damenhaico. Behind this lake there is a cirque glacier with a length of 2.5 km., which terminates at the bank of the lake. During the Tanbulang debris flow of 1964, the water level rose over ten meters, and the burst discharge reached 2000 m^3/s. The resulting huge debris flow flooded villages, and caused blockage of the Niyang River for 16 hours, and the highway traffic was closed for one week. This event took place at a location east of Lhasa.

Longda

In 1964, Longda glacier lake burst. The outburst flood washed out a huge amount of sediment which created a debris blockage 800 m long along the river, 200 m wide and 5 m deep on average on the Gyirongzangbo River, the source of the Trisuli River.

Chapter 10

Studied Glacial Lake

There are many glacial lakes in the Pumqu, Rongxer, Poiqu, Zangbuqin, Jilongcangbu, Majiacangbu, Daoliqu and Jiazhangangge basins in China Himalaya, but only selected number of them were surveyed or inspected. A Sino-Nepalese investigation during 1987 (LIGG/NEA/WECS 1988) carried out a field study of some selected glacial lakes in the Pumqu and Poiqu basin. The following is a brief account of each of these lakes as of 1987 field investigations.

10.1 ZONGGYACO LAKE

The Zonggyaco Lake is situated at the latitude 28^o 27' N and longitude 87^o 39' E at the headwaters of the Natanque River (Figure 10.1). The lake was dammed by Neoglaciation moraine. The lake is 2.5 km long, 1.391 sq. km of area with maximum depth of 25.5m and 0.0195 km^3 of water reserves. The Lake outlet is at 4,934 masl with the water level is at 4,935 masl The maximum free board of the end moraine dam is 27m. The outer slope of the moraine around 18 percent and the inner moraine slope is around 9.8 percent. A mother glacier (1.4 km long) is in contact with the lake and it covers an area of 1.37 sq. km (Figure 10.2). The distance between the main glacier and the back margin of the lake is only 3.5 km. Three series of end moraine ridges are found about one kilometre below the glacier, corresponding to the Little Ice Age moraines and the Zonggyaco Lake may be a relic of the Neoglaciation. This moraine has partly cemented and is made to form an undulating hilly landscape. The Zonggyaco Lake has two terraces: the first terrace is 2.5 m higher than the lake water level and is 5-10m in width and the second terrace is 4.5m higher than the lake water level and is 6-7m in width.

Figure 10.1: Elongated Zonggyaco Lake in the head water of Natanque River.

Figure 10.2: Scree slope and knife-edge crest beside Zonggyaco Lake

The lake water surface is situated far away from the back glacier and cannot affect greatly by the glacier advance. The mild slope, partly cemented and dry moraine dam represents the stable condition of the dam, the lake does not seems in the conditions for bursting. It is an end moraine-dammed lake in a stable and retreating state.

Chemical analysis showed that the lake water quality belongs to the HCO_3^- -- Ca^{++} type; total dissolved solids is 16.72 mg/1; and the pH 6.95. It is a freshwater lake nourished by snow melt water and precipitation.

10.2 RIOWPUCO LAKE

The Riwopuco Lake is named after the Riwo Village (7km west) and lies at latitude 28° 04'N and longitude 87° 38'E at an elevation of 5,470 masl (Figure 10.3). The Lake is 500m long and 100m wide with a surface area of 0.049 sq. km. The lake is elongated oval in shape and extended into the south-east direction. The lake is in contact with the cirque type hanging glacier in one side and other side dammed by lateral and end moraine.

Figure 10.3: Riowpuco Lake and its surroundings

The damming feature of the lake represents a recent end moraine. The dam is about 25m wide at the base and about 20m high. At 2 km downstream a 40m high breaching at the terminal moraine can be seen, which represents the outburst events in the past and reduced the size of the lake but no written documents. This lake is seems safe and even in out burst of this lake, there will be no damage at the downstream.

10.3 ABMACHIMAICO LAKE

The Abmachimaico Lake is situated at latitude 25^o 06'N and longitude 87^o 38'E at the headwaters of the Natangqu River (Figure 10.4). The lake is 1.8 km long and 0.3 km wide with an area of 0.565 sq. km. and 0.0194 km^3 of estimated water reserves. The lake was formed due to damming by Neoglaciation moraine. The total height of the dam is 118m with the elevation range of 5,220 masl and 5,102 masl. The freeboard of the lake is about 20m with the slope of about 12.5 percent and at dry side increases up to 29.5 percent.

The moraine ridge is about 250m away from the cliff of the glacier. The shape of the glacier is not well defined owing to long-term water erosion and destruction. There are some bedrocks protruded in the end moraine ridges.

Figure 10.4: Abmachimaico lake at the headwater of the Natangqu River

A small valley glacier having a length of 3.8km and 1.66 sq. km of area is connected at the left bank of the lake. The ice cliff of about 5.255m is exposed at the height of 40 to 50m at the lake side. An upheaval of frontal end of the ice cliff is recognised, which was formed by the pushing lake ice under the action of the advancing glacier in winter. From the actual movement it has been reported that the glacier advanced at least 3-4m in the past winter.

The water of Abmachimaico Lake, with HCO3- as preferential anion and Mg++ as preferential cation, belongs to the bicarbonate-magnesium type water. It is a freshwater lake with a total dissolved solid of 26.24mg/1, nourished by snow and ice melting water. Snow and glacial ice are also fresh water, having mineralization degrees than the water sample of the lake, with C1- as preferential anion, Ca++ and Mg++ as preferential cations.

The Abmachimaico Lake seems stable, the seasonal change of water is 0.3m, whereas the perennial water level change is 0.5-0.6m. The mother glacier is a normal movement glacier, and its advance cannot bring about a collapse because the advancing or retreating amplitude of the glacier is limited. The end moraine dam at the frontal margin has partly cemented and is in a stable state.

10.4 GELHAIPUCO LAKE

The Geilhaipuco Lake is located in the latitude 27º 58' N and longitude 87º 49' E at an elevation of 5,270 masl in the headwater of the Natangqu River (Figure 10.5). It is an end moraine-dammed lake, which was burst out on 21 September 1964, the details of the outburst is given in the Chapter 9. Before the burst, Gelhaipuco Lake was 1.4 km long with 0.548 sq. km area and about 25.45 million m3 of water reserves The water level of the lake was dropped by 40m after the lake burst in 1964. The slope of the exposed lake bed is 0.6% and it is 0.2 km away from the glacier margin. The present condition of the lake indicates stability. But if the glacier advances forward again, the possibility of another burst cannot be ruled out.

Figure 10.5: Gelhaipucho Lake and its hanging mother glacier

Generally, bank erosion and/or landslides at the narrow sections and large volume of debris were deposited on the wide valley. Large deposits of sand, gravel and big boulders are seen near its confluence with the Natangqu River. The riverbed has been eroded up to 6m at certain portions of the Gelhaipu Stream.

The lake is too small after outburst and less chances of further refilling of the lake. The lake can be considered safe. However, it is recommended that the lake should be monitored on a regular basis.

10.5 QANGZONKCO LAKE

The Qangzonkco Lake is situated at latitude 27º 56'N and longitude 87º 46'E at the headwaters of the Qumaqie Gully in the Natangqu River (Figure 10.6). In 1987 the lake was measured 2.1 km in length with an area of 0.763 sq. km. The lake dimension measured from the topographic map of 1974 shows only 1.4 km in length and 0.425 sq. km in area. From this it has the indication of lake expansion 0.026 sq. km per year and correspondingly, the glacier behind the lake has been retreated about 700m. The lake is dammed by end moraine ridge of the Little Ice Age.

The mother glacier in contact with the lake is a complex valley glacier with 6.6 km length and 10.091 m^2 of area. Its cliffy terminus has immersed into the lake, the visible height of the cliff is 20-25m. The upheaval belt formed by pushing lake ice under the frontal end of advancing glacier. There are huge ice masses in clusters floating on the surface of the lake, 1475 -1675m away from the ice cliff (Figure 10.6). The exposed height of the greatest ice mass is 4 to 5m and 3 to 4m in width would be 208-270m^3 in volume of ice. These might have originate only from the collapses of the retreating glacier.

The lateral moraine of the lake is forming 110 -190m higher than the water level. The moraine outer slope is 65 -110% and a lot of debris cones spread at the foot of the slope. At both sides of the adjacent glacial terminus, "dead ices" are exposed. These factors add to the instability of this lake. Three series of moraine ridges at the frontal end are found. There is an outlet at the right side of the end moraine ridge where the water flows slowly, but while it flows out the end moraine ridge, it rushes down along the slope. The inner two series end moraine ridges are fragmented: the gaps between ridges have become inter-lake passages due to long-term lake water erosion and destruction. The lake was divided into two lakes by three lines of end moraine ridges: the inner lake is the biggest one with a maximum depth of 69m; the outer lake has a maximum depth of 7 to 8m and covers an area of 0.020 sq. km. The volume of water stored in the lake is 0.0217 km^3 from the measurement in 1987

Figure 10.6: Frozen Qangzonkco Lake and its associated glacier

The mother glacier is retreating and some ice masses are continuously falling into the lake, though the quantity is not very large. Three series of end moraine ridges could play an important role in the stability of the lake. As for the inner series of ridges although their height exposed above the water surface are not very high, they could prevent safety to the outer dam. The depth of the lake water gradually decreases from inside to outside. The lake seems stable, however, if the glacier advanced to a large degree, or if the glacial tongue collapsed suddenly along with the ice bed, the strong shock waves produced and large amount of ice masses falling into the lake might lead to a burst. Therefore, it is felt necessary to monitor the dynamic changes of the mother glacier.

Analyses of the water samples of Qangzonkco Lake indicate that the lake water has HCO_3^- as preferential anion and Ca^{++} as preferential cation and it belongs to bicarbonate-calcium type water. The total dissolved solids is 34.90mg/1 and the pH is 6.75, thus being an excellent freshwater lake.

10.6 DAROCO LAKE NO. 5O191B0001 (IN THE POIQU BASIN)

According to Xudaoming's investigation, Daroco, a glacial erosion lake which is near the outlet of Congduipu Gully (LIGG/NEA/WECS 1988), had burst in 1955. The present field investigation indicates that the lake is 1.1 km long and covers an area of 0.517 km^2. It is a closed glacial erosion lake. The lake water level is 35 m below the outlet saddle. From this it is concluded that the lake probably never burst since its formation. The debris flow of 1955 might have been a burst of a glacier lake at the headwater of a branch gully flowing along the south side of Daroco Lake, or a debris flow formed by glacier ablation. Rather fresh debris flow sediments can be seen in that valley.

Daroco Lake is a beautiful ice-free body of water with no discernible inflow, now at approximately 4390 m a.s.1. A former outlet (the east saddle) now dry, is approximately 30 m above the lake water level. There is some evidence of exposed beaches indicating receding lake levels. Its catchment does not include any glacier, and during the inspection in mid June, not much snow was present on the peaks immediately around it. Inflow creek beds were dry.

It is concluded that, barring an extraordinary event, this, not being a glacier lake today, is not a potential source of outburst floods. However, the large moraine east of the lake shows some signs of small local rock slides along Congduipu Gully.

10.7 LAKE NO.5O191B004 (IN POIQU BASIN)

Glacier Lake No. 5O191B004 of the Poiqu River lies across the Congduipu Main Gully of the Poiqu River, latitude 28º12' N and longitude 85º51' E. The altitude of lake surface is approximately 4400 m a.s.1. It is 0.8 km in length, the area being 0.332 km^2 and the water reserves estimated is 0.0083 km^3. It is an end moraine-dammed lake with end moraine ridge of the Little Ice Age.

The adjacent glacier behind the lake is Glacier No.21 (LIGG/NEA/WECS 1988) in the Poiqu River. It is 5.5 km long and covers an area of 5.01 km^2, being a cirque-valley glacier. The glacial terminus connects to the lake bank through an ice cliff. The glacier consists of two firn basins that on converging form an ice fall. The ice layer is broken and the glacial tongue, with moraine material covering its surface, is gentle. The glacier behind the lake has steep slopes and well-developed crevasses, and thus could collapse.

The lake moraines bounding it have partially blocked the drainage flow from upper valley reaches of the Congduipu Main Gully, where other lakes may also exist. The gully flow around Lake No.5 (LIGG/NEA/WECS 1988) moraine is substantially higher than that overflowing its end moraine. Between Lake No.5 (LIGG/NEA/WECS 1988) moraine and the larger and higher latter moraine separating the two valleys (Congduipu and Jiapu), flows the river which is eroding the toe of the latter moraine. This moraine is very steep and high and right across the lake where the obstruction is. It has suffered severe undercutting and loose material is falling on the river.

Although small, it is considered that Lake 5O191B004 is potentially dangerous as it has a steep glacier as its source; is overflowing; is now constricting the Congduipu Main Gully channel; a gully blockage may occur if large moraine landslides develop (a distinct possibility); being at a relatively low elevation, the lake exhibits an ice-free surface for longer periods, thus longer exposure to serious water surface disturbances; and, its drainage valley is relatively straight and steep, with Nyalam just about 18 km downstream.

It is concluded that, pending further study, Lake 5O191B004 is potentially hazardous and deserves further, close surveys, investigations and monitoring. These should also include a survey of the moraines, lakes and glaciers northwest and upstream of the lake whose drain waters constitute the source of the Congduipu Gully.

10.8 LAKE NO. 5O191B0026 (IN POIQU BASIN)

Lake No. 11(LIGG/NEA/WECS 1988) at approximately 5000 masl is smaller than Lake No. 5O191B0026 and lies S-SW and not far from it. This lake does not seem to have a major feeder nor was a drainage outlet observed. It is likely that it flows into Lake 5O191B0027 along a very mild channel. It is perhaps a small shallow lake with a remote likelihood of bursting as it is trapped around very wide and flat morainic remains.

10.9 LAKES NO. 5O191B0027 AND 5O191B0028 (IN POIQU BASIN)

Lake 5O191B0027 at approximately 5000 masl, is about one fifth of the surface area of Lake 5O191B0030, a few hundred meters southwest from the latter, and almost circular in shape. It has a permanent, very wide overflow drainage channel flowing into drain from Lake 5O191B0030 (Jiapu Gully). The overflow waters are very clean, which is not the case of the overflow from Lake 5O191B0030 as pointed out. The drain channel is long and has a relatively mild slope. No glaciers lie directly around the lake; it might be fed by a seepage through a western moraine holding 5O191B0028. Its terminal moraine in the east is low and flat.

Lake 5O191B0028, due west of Lake 5O191B0027, seems to be smaller and is perhaps higher in elevation. No major glacier is around it and it is surrounded by talus; snow and ice may fall from the higher sections of the surrounding range.

Based on this scanty intbrmation, it is concluded that the only possible threat to Lake 5O191B0027 would exist if somehow Lake 5O191B0028 bursts, a remote possibility. Moreover the lake volume seems to be relatively small and the drop in elevation from lake waters to valley is of the order of 20 to 25 m. The possibility of bursting is then considered to be nonexistent.

10.10 LAKE NO.5O191B0030 (IN POIQU BASIN)

Glacier Lake 5O191B0030 in the Poiqu (Bhote-Sun Koshi) River, at approximately 5030 masl, is situated at the headwaters of the Jiapu Gully, the northern tributary of Congduipu Gully; its latitude is 28º19 ' N and longitude 85º50 ' E. At present the lake is 2.1 km long and covers an area of 1.684 km^2, being the largest end moraine-dammed lake in the Poiqu Basin.

Calculated from 1974 aerial photograph and corresponding map, the lake was 1.3 km long and had an area of 0.875 km². It was shown on those records that a sandy stretch of land, 0.5 km in length, is located between the upper margin of the lake and the glacial terminus. In addition, there was a small lake with an area of 0.04 km², 0.3 km in length, lying in the branch gully of the big lake to the west. This investigation found that the glacier behind Lake 5O191B0030 has retreated 0.3 km since 1974, and the glacial terminus has connected to the lake waters, the former sandy land being now submerged by the raised lake water. The small lake is now connected to the big lake. Thus, the length of Lake 5O191B0030 and its area have increased by 0.8 km and 0.809 km² respectively, and its water level has also correspondingly raised. If the average depth of the glacier lake is 30 m, its water reserve may reach 0.0505 km³ (no measurements of depth were made during the inspection).

There is a complex valley glacier with a length of 9.5 km and an area of 15.41 km² developed behind this lake. This glacier originated from the southeastern side of Mt. Xixabangma and consists mainly of two ice-flows. 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 of Glacier No.35 (LIGG/NEA/WECS 1988) and its terminus is 2900 m; the positive difference of glaciation is 2280 m, whereas the negative difference of glaciation is 630 m. The glacier is mainly nourished by snowfall, snow-avalanche and snow drift, and under the influences of the climate, advances or retreats.

The end moraine ridge at the frontal margin of the lake was formed in the Little Ice Age. As compared with the outside river bed the altitude difference is approximately 80 m, and the slope on the dry side is 25%. The moraine ridges, ranging from 5050 to 5075 masl, have not cemented into rocks and have a poor stability, because they were formed in recent times.

Lake 5O191B0030 is overflowing at the south end and also permanent seepage was observed at the foot of the terminal moraine. Such seepage and overflow have dug their own channels and seem to have been there for some time. Overflow is along the moraine in two steps, the lower one being more abrupt, for a total drop from lake to valley of about 40 to 50 m. Seepage water is very clean whereas overflow water is milky. This lake seems to be a threatening one and is cause for concern. Based on qualitative observations during visit, it is over-flowing; it is seeping; the dead-ice area seems to be receding quickly; the two bodies of water being connected, an ice or rock fall from the adjacent Glacier No.34 (LIGG/NEA/WECS 1988) over the small bay may create disturbances powerful enough to cause a burst of the terminal moraine.

It is then preliminarily concluded that Lake 5O191B0030 is a potential candidate for creating a GLOF, and that therefore it deserves further and deeper investigations, surveys and monitoring, including its glaciers.

The water of Lake 5O191B0030 with HCO_3^- as preferential anion and Mg^{++} as preferential cation, belongs to bicarbonate-magnesium-type water. The total dissolved solids is 25.46 mg / 1; pH 7.21, being a low-mineralized fresh water lake. The lake was found to be frozen over in early June but its margin cover had partly melted. From this it is inferred that the lake is frozen over in winter and spring, its ice thickness likely reaching 0.8-1.0 m.

10.11 KUNGCO LAKE NO. 5O191B0045 (IN POIQU BASIN)

This is the largest (surface wise) water body within the basin below or above Lake 5O191B0030, measuring approximately 2.7 km along its NE-SW axis. It is surrounded by moraines (On NE and SW corners) and relatively mild sloping hills.

There are no visible glaciers within its catchment area and no inflow was observed along the S, W and N perimeters. The west lake shore was inspected and it displays a steep beach formed of sand and, mostly, of boulders of up to about 1 foot in diameter. High water marks along this beach are now from 10 to 15 m, above the current lake surface.

The above evidence indicates that a deeper lake was present but has receded over the last decades, as the beach marks suggest; the moraine saddles are much higher than the water surface and it is possible that in former times it drained south along Jiapu Gully east of Lake 5O191B0030, as a higher moraine separates those two features.

It is concluded that this, not being a glacier lake today, poses no threat as far as bursting. Evidence points to this being a dying lake perhaps not too deep at this time.

10.12 GANGXICO LAKE NO. 5O191C0011 (IN POIQN BASIN)

This lake, at approximately 5300 masl, in the headwaters of a basin lying north of the Congduipu Gully and flowing into the Poiqu River in a general east direction (thus its water following a longer path into Nepal), was inspected for just a few minutes. It was reached from the south across steep moraines between this lake and Kungco.

The 1.5 km 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. Xixabangma, due east of Gangxico Lake. The frozen surface exhibited a number of icebergs or trapped glacier ice chunks spread all over. No evidence of overflow was seen from the only vintage point from which observations were made.

The quick observations made do not allow for even a preliminary conclusion on this lake's potential hazard. 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.

It is, therefore, concluded that further investigation of glacier and lake, particularly of the exit area of this lake, is necessary to fully assess its GLOF potential.

Chapter 11

Potentially Dangerous Glacial Lakes

On the basis of actively retreating glaciers and other criteria, the potentially dangerous glacial lakes were identified using the spatial and attribute database complemented by multi-temporal remote-sensing data sets. Medium- to large-scale aerial photographs were used for detailed geomorphic studies and evaluation of the active glaciers and potentially dangerous lakes.

In general, based on geomorphological characteristics, glacial lakes can be grouped into three types: glacial erosion lakes, glacial cirque lakes, and moraine-dammed lakes. The former two types of glacial lakes occupy the lowlands or emptying cirques eroded by ancient glaciers. These glacial lakes are more or less located away from present-day glaciers and the downstream banks are usually made of bedrock or covered with a thinner layer of loose sediment. Both of these glacial lakes do not generally pose an outburst danger. On the other hand, the moraine-dammed glacial lakes have the potential for bursting. A standard index to define a lake that is a source of potential danger because of possible bursting does not exist.

Moraine-dammed glacial lakes, which are still in contact or very near to the glaciers, are usually dangerous. In most of the literature/reports, the term ‘glacial lake’ is used for such lakes, and the term ‘glacial lakes’ used for glacier erosion lakes and glacier cirque lakes. The present study defines all the lakes formed by the activity of glaciers as ‘glacial lakes’. Moraine-dammed glacial lakes are usually dangerous. These glacial lakes were partly formed between present-day glaciers and Little Ice Age moraine. The depositions of Little Ice Age moraines are usually about 300 years old, form high and narrow arch-shaped ridges usually with a height of 20–150m, and often contain dead glacier ice layers beneath them. These end moraines are loose and unstable in nature. The advance and retreat of the glacier affect the hydrology between the present-day glacier and the lake dammed by the moraines. Sudden natural phenomena with a direct effect on a lake, like ice avalanches or rock and lateral moraine material collapsing on a lake, cause moraine breaches with subsequent lake outburst events. Such phenomena have been well known in the past in several cases of moraine-dammed lakes, although the mechanisms at play are not fully understood.

11.1 CRITERIA FOR IDENTIFICATION

The criteria for identifying the potentially dangerous glacial lakes are based on field observations, processes and records of past events, geomorphological and geo-technical characteristics of the lake and surroundings, and other physical conditions. The potentially dangerous lakes were identified based on the condition of lakes, dams, associated mother glaciers, and topographic features around the lakes and glaciers.

Rise in lake water level

In general the lakes which have a volume of more than 0.01 km^3 are found to have past events. A lake which has a larger volume than this, is deeper, with a deeper part near the dam (lower part of lake) rather than near the glacier tongue, and has rapid increase in lake water volume is an indication that a lake is potentially dangerous.

Activity of supraglacial lakes

Groups of closely spaced supraglacial lakes of smaller size at glacier tongues merge as time passes and form bigger lakes. These activities of supraglacial lakes are an indication that the lakes are becoming potentially dangerous.

Position of lakes

The potentially dangerous lakes are generally at the lower part of the ablation area of the glacier near to the end moraine, and the mother glacier should be sufficiently large to create a potentially dangerous lake environment. Regular monitoring needs to be carried out for such lakes with the help of multi-temporal satellite images, aerial photographs, and field observations.

In general, the potentially dangerous status of moraine-dammed lakes can be defined by the conditions of the damming material and the nature of the mother glacier. The valley lakes with an area bigger than 0.1 sq. km. and a distance less than 0.5 km from the mother glacier of considerable size are considered to be potentially dangerous. Cirque lakes even smaller than 0.1 sq. km. associated (in contact or distance less than 0.5 km) with steep hanging glaciers are considered to be potentially dangerous. Even the smaller size steep hanging glacier may pose a danger to the lake.

Dam conditions

The natural conditions of the moraine damming the lake determine the lake stability. Lake stability will be less if the moraine dam has a combination of the following characteristics:

- narrower in the crest area
- no drainage outflow or outlet not well defined
- steeper slope of the moraine walls
- ice cored
- very tall (from toe to crest)
- mass movement or potential mass movement in the inner slope and/or outer slope
- breached and closed in the past and refilled again with water
- seepage flow at moraine walls

A moraine-dammed lake, which has breached and closed subsequently in the past and has refilled again with water, can breach again. Ayaco Lake in the Pumqu Basin burst out in 1968, 1969, and 1970, and in 1980s it was refilled again with water and poses danger. In fact, there is a less water volume than before, based on the ASTER image of Feb. 21 and Oct. 13, 2001. So, regular monitoring of such lakes is necessary using multi-temporal satellite images.

Condition of associated mother glacier

Generally, the bigger valley glaciers with tongues reaching an elevation below 5,000 masl have well-developed glacial lakes. Even the actively retreating and steep hanging glaciers on the banks of lakes may be a potential cause of danger. The following general characteristics of associated mother glaciers can create danger to moraine-dammed lakes:

- hanging glacier in contact with the lake,
- bigger glacier area,
- fast retreating,
- debris cover at glacier tongue area,
- steep gradient at glacier tongue area,
- presence of crevasses and ponds at glacier tongue area,
- toppling/collapses of glacier masses at the glacier tongue, and
- ice blocks draining to lake.
- hanging glacier in contact with the lake

Physical conditions of surroundings

Besides moraines, mother glaciers, and lake conditions, other physical conditions of the surrounding area as given below may also cause the lake to be potentially dangerous:

- potential rockfall/slide (mass movements) site around the lake which can fall into the lake suddenly
- snow avalanches of large size around the lake which can fall into the lake suddenly
- neo-tectonic and earthquake activities around or near the lake area
- climatic conditions of successive years being a relatively wet and cold year followed by a hot and wet or hot and arid year
- very recent moraines damming the lake at the tributary glaciers that used to be just a part of a former complex of valley glacier middle moraines as a result of the fast retreat of a complex mother valley glacier
- sudden advance of a glacier towards the lower tributary or mother glacier having a well-developed lake at its tongue

11.2 MAJOR GLACIAL LAKES ASSOCIATED WITH THE GLACIERS

For identification of potentially dangerous glacial lakes, the glacial lakes associated with glaciers like supraglacial lakes and/or dammed by lateral moraine or end moraine with an area larger than 0.02 sq. km. have been considered and they have been defined as major glacial lakes. The area of the inventoried glacial lakes is larger than 0.003 sq. km. There are 824 such glacial lakes in the Himalayan-China Region. Among these lakes, 199 glacial lakes having an area larger than 0.02 sq. km. Most of the major glacial lakes are in contact with or at a distance of less than 500m away from the glaciers and some of them are 1,500m away from the glaciers.

Major glacial lakes associated with the glaciers were shown in the Tables (from Table11.1, to Table 11.8)

Table 11.1: Major glacial lakes associated with the glaciers in the Jiazhagangge basin

Lake Number	Lake name	Elevation (masl)	Type	Area (m^2)	Associated glacier No.	Distance to Glacier (m)
Jiazhagangge_2		5200	M	54509.898		0
Jiazhagangge_3		5400	M	34642.965		0
Jiazhagangge_4		5400	M	21294.359		0
Jiazhagangge_7		5410	M	36408.766		0
Jiazhagangge_8		5600	M	22262.645		0
Jiazhagangge_9		5420	M	63449.969		0
Jiazhagangge_10		5400	M	47456.273		0
Jiazhagangge_12		5500	M	63086.309		0
Jiazhagangge_13		5500	M	68921.520		0
Jiazhagangge_14		5540	M	24313.445		0

Table 11.2: Major glacial lakes associated with the glaciers in the Daoliqu basin						
Lake Number	Lake name	Elevation (masl)	Type	Area (m^2)	Associated glacier No.	Distance to Glacier (m)
Daoliqu_1		4900	M	85526.152		0
Daoliqu_2		5500	M	20294.750		0
Daoliqu_2		5010	M	33157.367		0
Daoliqu_3		5200	M	93291.242		0
Daoliqu_4		4970	M	83141.234		0

Table 11.3: Major glacial lakes associated with the glaciers in the Majiacangbu basin						
Lake Number	Lake name	Elevation (masl)	Type	Area (m^2)	Associated glacier No.	Distance to Glacier (m)
Majiacangbu_4		5200	M	16583.555		122
Majiacangbu_6		5280	M	100395.359		
Majiacangbu_7		5100	M	444399.781		137
Majiacangbu_10_06		4740	S	22738.891		
Majiacangbu_11		5260	E	10647.141		
Majiacangbu_12		5300	E	18044.191		
Majiacangbu_13		5200	E	270137.000		
Majiacangbu_14		5240	E	9720.000		
Majiacangbu_15		5220	E	24662.551		
Majiacangbu_17		5220	E	624406.375		
Majiacangbu_18		5500	E	38321.016		
Majiacangbu_20		5820	C	115527.563		877
Majiacangbu_21		5460	V	24222.047		
Majiacangbu_22		5580	E	40947.148		
Majiacangbu_23		5820	V	23936.281		
Majiacangbu_24		5600	V	64860.352		
Majiacangbu_29		5400	E	13529.707		535
Majiacangbu_35		5760	C	75447.922		
Majiacangbu_36		5760	C	112178.609		475
Majiacangbu_37		5620	E	54199.594		289
Majiacangbu_40		5570	M	127984.016		
Majiacangbu_43		5390	M	21858.672		22
Majiacangbu_45		5650	M	174273.031		
Majiacangbu_47		5740	C	285980.688		76
Majiacangbu_50		5640	M	80668.539		19
Majiacangbu_51		5580	M	105701.484		30
Majiacangbu_52		5520	V	62516.578		463
Majiacangbu_54		5530	M	274859.750		
Majiacangbu_55		5460	M	86256.875		94
Majiacangbu_56		5430	M	72709.148		20
Majiacangbu_57		5230	M	263174.969		297

Majiacangbu_58		5420	M	121215.836		229
Majiacangbu_59		5340	M	451944.594		
Majiacangbu_60		5300	M	35973.516		282
Majiacangbu_61		5580	E	21643.500		329
Majiacangbu_63		5420	M	51884.430		291

Table 11.4: Major glacial lakes associated with the glaciers in the Jilongcangbu basin

Lake Number	Lake name	Elevation (masl)	Type	Area (m^2)	Associated glacier No.	Distance to Glacier (m)
Jilongcangbu_2		5470	M	75547.453	35	0
Jilongcangbu_24		5460	M	218432.887	60	103
Jilongcangbu_25		4760	M	55114.688	61	0
Jilongcangbu_26		5130	M	27780.355	65	106
Jilongcangbu_27		5060	M	36228.043	66	250
Jilongcangbu_28		5000	M	88078.664	72	161
Jilongcangbu_33		4740	M	37840.582	96	0
Jilongcangbu_34		4750	M	84860.887	97	150
Jilongcangbu_39		4640	M	94876.617	104	0
Jilongcangbu_40		5000	M	34420.484	106	0
Jilongcangbu_42		4520	M	21931.719	110	0
Jilongcangbu_44		4440	M	163726.547	112	427
Jilongcangbu_45		4440	M	85468.496	113	0
Jilongcangbu_46		4710	M	83977.621	115	91
Jilongcangbu_47		4760	M	84818.227	118	0
Jilongcangbu_48		4440	M	424676.266	120	340
Jilongcangbu_49		5240	M	26131.758	145	0
Jilongcangbu_5		5230	M	35474.051	42	0
Jilongcangbu_51		5260	M	62340.711		143
Jilongcangbu_56		4420	M	112087.586	156	0
Jilongcangbu_65		5040	M	28077.102	175	253
Jilongcangbu_66		5340	M	61747.719	179	254
Jilongcangbu_67		5240	M	62909.023	178	89

Table 11.5: Major glacial lakes associated with the glaciers in the Poiqu basin						
Lake Number	**Lake name**	**Elevation (masl)**	**Type**	**Area** (m^2)	**Associated glacier No.**	**Distance to Glacier (m)**
Poiqu_11		5600	M	20426.211	25	952
Poiqu_15		5320	M	67326.074	26	1430
Poiqu_23		5110	M	190116.684	33	171
Poiqu_26		5100	M	3136591.234	37	0
Poiqu_45		5220	M	261166.590	42	86
Poiqu_46		5300	M	113020.148	44	128
Poiqu_47		5340	M	93728.281	45	256
Poiqu_49		5400	M	144313.371	46	242
Poiqu_54		5290	M	3373971.188	47	0
Poiqu_58		5590	M	44916.813	57	0
Poiqu_59		5560	M	168281.918	65	0
Poiqu_6		4370	M	174912.930	20	431
Poiqu_60		5360	M	371695.113	74	0
Poiqu_61		5360	M	26423.887	77,78	2564
Poiqu_63		5510	M	610468.742	77,78	0
Poiqu_64		5560	M	228631.520	82	150
Poiqu_65		5380	M	594534.387	85	0
Poiqu_66		5360	M	161223.844	86	40
Poiqu_67		5260	M	239204.992	89	356
Poiqu_7		4760	M	41795.320	22	100
Poiqu_82		4660	M	198277.348	113	467
Poiqu_9		5620	M	28406.930	25	422

Table 11.6: Major glacial lakes associated with the glaciers in the Pumqu basin						
Lake Number	**Lake name**	**Elevation (masl)**	**Type**	**Area** (m^2)	**Associated glacier No.**	**Distance to Glacier (m)**
Pumqu_A_6		4520	M	323329.852	13	183
Pumqu_B_18		4880	M	249095.203	10	0
Pumqu_B_19		5660	M	607776.406	21	0
Pumqu_B_20		5760	M	42344.344	22	277
Pumqu_B_21		5540	M	109258.676	28	550
Pumqu_B_22		5740	M	26820.324	35	188
Pumqu_B_23		5520	M	180811.164	37	1255
Pumqu_B_24		5520	M	60868.234	37	796
Pumqu_C_12		5780	M	20785.660	175	494
Pumqu_C_3		5060	M	150840.078	5	138
Pumqu_C_5		5740	M	24062.539	39	934
Pumqu_D_1		5620	M	54898.176	12	480
Pumqu_D_11		5800	M	37886.203	43	377
Pumqu_D_12		5130	M	1261710.348	62	0
Pumqu_D_13		5120	M	47060.957	62	1885
Pumqu_D_21		5540	M	311191.004	80	586
Pumqu_D_22		5640	M	52745.582	82	195
Pumqu_D_23		5620	M	47816.902	90	411
Pumqu_D_25		5560	M	50361.320	92	540
Pumqu_D_26		5520	M	180939.219	98	0
Pumqu_D_27		5560	M	158659.488	102	0
Pumqu_D_28		5530	M	575223.852	109	0
Pumqu_D_30		5380	M	4135052.359	116	0
Pumqu_D_5		5680	M	105327.086	21	497
Pumqu_E_2		5580	M	213555.891	7	249
Pumqu_G_1		5800	M	79914.852	7	34
Pumqu_G_10		5100	M	380861.492	25,26	500
Pumqu_G_11		5290	M	508882.359	28	0
Pumqu_G_12		5370	M	478298.086	31	0
Pumqu_G_13		5260	M	308047.141	32	0
Pumqu_G_14		5380	M	121814.117	36	239
Pumqu_G_15		5240	M	83987.180	37	132
Pumqu_G_16		5520	M	913580.461	91	0
Pumqu_G_17		5590	M	722764.633	96	0

Pumqu_G_18		5840	M	68949.859	100	90
Pumqu_G_19		5390	M	1112609.695	106,107,108	0
Pumqu_G_2		5600	M	105100.492	8	631
Pumqu_G_20		5630	M	65149.953	111	486
Pumqu_G_21		5500	M	48913.328	112,113	615
Pumqu_G_22		5570	M	47280.383	112,113	69
Pumqu_G_24		5120	M	23969.344	121	2136
Pumqu_G_25		5140	M	747675.188	121	0
Pumqu_G_26		5210	M	664339.641	122	582
Pumqu_G_27		5520	M	117785.813	124	382
Pumqu_G_28		5730	M	26749.703	127	395
Pumqu_G_31		5640	M	44012.305	128	191
Pumqu_G_32		5620	V	79747.234	128	976
Pumqu_G_33		5600	V	207492.063	128	1621
Pumqu_G_34		5660	M	79410.102	135	217
Pumqu_G_35		5700	M	99144.000	137	372
Pumqu_G_37		5400	M	190377.039	150	43
Pumqu_G_38		5500	M	545509.766	152	0
Pumqu_G_39		5640	M	21314.016	153	711
Pumqu_G_40		5580	M	34489.820	159	665
Pumqu_G_6		5260	M	213563.320	15	249
Pumqu_G_7		5520	M	38923.109	20	189
Pumqu_G_8		5240	M	538032.070	22	263
Pumqu_G_9		5300	M	64239.773	24	159
Pumqu_H_16		5500	M	846200.234	21	153
Pumqu_H_17		5260	M	227740.625	22	110
Pumqu_H_18		5410	M	67753.125	23	0
Pumqu_H_19		5350	M	73880.883	25	95
Pumqu_H_25		5340	M	174391.227	35	0
Pumqu_H_26		5030	M	836525.602	37	0
Pumqu_H_27		4840	V	109990.914	44	5391
Pumqu_H_29		4880	V	341585.375	44	2358
Pumqu_H_30		5320	M	183870.578	42	0
Pumqu_H_33		5200	M	371096.040	44	0
Pumqu_H_37		5150	M	62392.891	46	0
Pumqu_H_39		5200	M	31450.328	51	0
Pumqu_H_40		5180	M	29962.813	52	79
Pumqu_H_41		5210	M	77771.734	52	0

Pumqu_H_42		5360	M	65760.984	55	0
Pumqu_H_48		5180	M	182022.859	57	452
Pumqu_H_49		5160	M	78079.023	59	86
Pumqu_H_50		5040	M	161787.305	60	92
Pumqu_H_54		4830	M	43872.039	64	196
Pumqu_H_9		5680	M	100992.383	2	113
Pumqu_I_12		5200	M	33367.430	15	260
Pumqu_I_13		5060	M	172781.492	17	314
Pumqu_I_16		5180	M	594393.570	20	72
Pumqu_I_17		4960	V	1458918.719	22	2161
Pumqu_I_18		5080	M	315869.459	22	60
Pumqu_I_24		5240	M	47510.484	26	695
Pumqu_I_25		5240	M	128968.148	26	215
Pumqu_I_28		5690	M	44505.227	34	0
Pumqu_I_33		5290	M	249191.391	42	0
Pumqu_I_34		5100	M	901023.234	48	0
Pumqu_I_35		5330	M	22635.258	52	0
Pumqu_I_37		5240	M	101773.477	55	144
Pumqu_I_40		5360	M	132085.383	62	91
Pumqu_I_50		5170	M	37941.875	73	109
Pumqu_I_55		4880	M	80342.797	74	424

Table 11.7: Major glacial lakes associated with the glaciers in the Rongxer basin						
Lake Number	**Lake name**	**Elevation (masl)**	**Type**	**Area** (m^2)	**Associated glacier No.**	**Distance to Glacier (m)**
Rongxer Qu_B_12		5420	M	30792.816	9	376
Rongxer Qu_B_15		5340	M	117012.414	14	72
Rongxer Qu_B_16		5340	M	167321.137	19	0
Rongxer Qu_B_17		5450	M	44328.441	20	73
Rongxer Qu_B_18		5420	M	40069.227	21	33
Rongxer Qu_B_19		5380	M	38957.609	24	181
Rongxer Qu_B_23		5240	M	40724.531	27	768
Rongxer Qu_B_24		5190	M	52872.102	29	0
Rongxer Qu_B_30		5280	M	27543.676	37	397
Rongxer Qu_B_46		5390	M	260082.199	55	381
Rongxer Qu_B_47		5280	M	74474.289	58	195
Rongxer Qu_B_52		5270	M	255866.973	65	298
Rongxer Qu_B_7		5340	M	122856.172	6	120
Rongxer Qu_C_21		5360	M	182961.746	24	121
Rongxer Qu_C_28		5350	M	242590.273	34	0
Rongxer Qu_C_29		5340	M	28999.281	34	891
Rongxer Qu_C_39		5050	M	557639.969	47	0
Rongxer Qu_C_43		5110	M	793293.465	56	0
Rongxer Qu_C_53		5370	M	79242.992	74	186
Rongxer Qu_C_55		5240	M	533354.059	75	0
Rongxer Qu_C_57		5080	M	320532.637	76	0
Rongxer Qu_C_58		4980	M	27609.633	76	84
Rongxer Qu_C_61		4700	M	23613.133	85	106
Rongxer Qu_C_67		5100	M	114723.695	91	0
Rongxer Qu_C_68		5170	M	652607.195	91	0
Rongxer Qu_C_69		5100	M	50855.555	91	0
Rongxer Qu_C_70		5200	M	72937.059	92	0
Rongxer Qu_C_71		5100	M	322636.543	92	0
Rongxer Qu_C_8		5160	M	54339.563	15	263

Table 11.8: Major glacial lakes associated with the glaciers in the Zangbuqin basin						
Lake Number	**Lake name**	**Elevation (masl)**	**Type**	**Area (m^2)**	**Associated glacier No.**	**Distance to Glacier (m)**
Zangbuqin_2		5390	M	24469.109	25	238
Zangbuqin_5		4771	M	94743.191	62	41

11.3 POTENTIALLY DANGEROUS GLACIAL LAKES

Based on the analysis of inventory data using different criteria and the study of satellite images, 77 glacial lakes are identified as potentially dangerous lakes in the Himalayan-China Region. Out of these there are three glacial lakes (i.e. Gelhaipuco, Ayaco, and Jinco) with past outburst events. The identified potentially dangerous lakes are recommended for further detailed investigation and field survey to understand their activity (Table 11.9).

Table 11.9: Potentially dangerous glacial lakes of Himalaya-China Region identified from the inventory and recommended for further investigation and field survey					
Lake number	**Latitude**	**Longitude**	**Altitude(masl)**	**Length (m)**	**Area (m2)**
Jiazhagangge basin					
Jiazhagangge_2			5200	270	54509.90
Majiacangbu					
Majiacangbu_7			5100	1159	444399.79
Majiacangbu_6			5280	494	100395.36
Majiacangbu_40			5570	567	127984.02
Majiacangbu_45			5650	590	174273.03
Majiacangbu_51			5580	587	105701.48
Majiacangbu_54			5530	712	274859.75
Majiacangbu_55			5460	324	86256.88
Majiacangbu_56			5430	427	72709.15
Majiacangbu_57			5230	951	263174.97
Majiacangbu_58			5420	620	121215.84
Majiacangbu_59			5340	1447	451944.60
Jilongcangbu basin					
Jilongcangbu_24	85°24.61 ’E	28°40.54 ’N	5460	806	218432.89
Jilongcangbu_48	85°31.14 ’E	28°28.07 ’N	4440	1238	424676.27
Poiqu basin					
Poiqu_26	85°50.49 ’E	28°19.01 ’N	5100	3216	3136591.23
Poiqu_54	85°52.58 ’E	28°21.62 ’N	5290	3636	3373971.19
Poiqu_59	86°15.44 ’E	28°22.49 ’N	5560	634	168281.92
Poiqu_60	86°13.48 ’E	28°20.99 ’N	5360	1293	371695.11
Poiqu_63	86°11.47 ’E	28°20.14 ’N	5510	1416	610468.74
Poiqu_64	86°9.51 ’E	28°19.27 ’N	5560	697	228631.52
Poiqu_65	86°9.48 ’E	28°18.22 ’N	5376	2064	594534.39
Poiqu_66	86°9.09 ’E	28°17.66 ’N	5360	856	161223.84
Poiqu_67	86°7.87 ’E	28°17.64 ’N	5260	1023	239204.99
Pumqu basin					
Pumqu_C_4	87°3.02 ’E	28°12.38 ’N	5090	1904	572276.72
Pumqu_D_12	86°34.91 ’E	28°11.95 ’N	5130	2429	1261710.35
Pumqu_D_28	86°22.81 ’E	28°23.72 ’N	5530	968	575223.85
Pumqu_D_30	86°18.23 ’E	28°22.64 ’N	5380	5611	4135052.36
Pumqu_G_10	88°19.25 ’E	28°0.37 ’N	5100	1429	380861.49

Pumqu_G_11	88°17.26 ’E	28°1.04 ’N	5290	1402	508882.36
Pumqu_G_12	88°15.47 ’E	28°0.67 ’N	5370	1235	478298.09
Pumqu_G_13	88°14.45 ’E	28°0.36 ’N	5260	968	308047.14
Pumqu_G_16	88°4.42 ’E	27°56.96 ’N	5520	1576	913580.46
Pumqu_G_17	88°4.03 ’E	27°56.16 ’N	5590	1387	722764.63
Pumqu_G_19	88°0.27 ’E	27°55.83 ’N	5390	3343	1112609.70
Pumqu_G_20	87°59.54 ’E	27°55.54 ’N	5630	306	65149.95
Pumqu_G_25	87°55.83 ’E	27°57.11 ’N	5140	2359	747675.19
Pumqu_G_26	87°54.49 ’E	27°57.07 ’N	5210	1755	664339.64
Pumqu_G_27	87°53.76 ’E	27°56.59 ’N	5520	596	117785.81
Pumqu_G_28	87°52.25 ’E	27°57.86 ’N	5730	384	26749.70
Pumqu_G_31	87°52.10 ’E	27°58.13 ’N	5640	357	44012.31
Pumqu_G_32	87°52.60 ’E	27°58.19 ’N	5620	800	79747.23
Pumqu_G_33	87°53.06 ’E	27°58.13 ’N	5600	727	207492.06
Pumqu_G_37	87°37.41 ’E	28°10.06 ’N	5400	675	190377.04
Pumqu_G_38	87°38.39 ’E	28°11.68 ’N	5500	1479	545509.77
Pumqu_G_39	87°38.44 ’E	28°12.29 ’N	5640	244	21314.02
Pumqu_G_8	88°21.24 ’E	28°1.42 ’N	5240	1826	538032.07
Pumqu_H_16	87°35.54 ’E	28°13.77 ’N	5500	2178	846200.23
Pumqu_H_17	87°34.65 ’E	28°13.70 ’N	5260	886	227740.63
Pumqu_H_23	87°28.27 ’E	28°12.78 ’N	4850	4655	1326268.61
Pumqu_H_25	87°33.60 ’E	28°12.39 ’N	5340	713	174391.23
Pumqu_H_26	87°33.68 ’E	28°10.70 ’N	5030	2344	836525.60
Pumqu_H_27	87°25.07 ’E	28°9.89 ’N	4840	647	109990.91
Pumqu_H_29	87°26.70 ’E	28°9.60 ’N	4880	1697	341585.38
Pumqu_H_30	87°28.77 ’E	28°10.36 ’N	5320	751	183870.58
Pumqu_H_33	87°28.13 ’E	28°8.84 ’N	5200	1156	371096.04
Pumqu_H_50	87°35.23 ’E	28°6.92 ’N	5040	663	161787.31
Pumqu_I_17	87°39.19 ’E	28°6.86 ’N	4960	2651	1458918.72
Pumqu_I_18	87°36.94 ’E	28°7.10 ’N	5080	931	315869.46
Pumqu_I_28	87°52.19 ’E	28°1.49 ’N	5690	594	44505.23
Pumqu_I_33	87°48.64 ’E	27°57.87 ’N	5290	1059	249191.39
Pumqu_I_34	87°46.21 ’E	27°55.61 ’N	5100	2594	901023.23
Rongxer Qu basin					
Rongxer Qu_B_15	86°11.20 ’E	28°16.20 ’N	5340	572	117012.41
Rongxer Qu_B_16	86°11.74 ’E	28°14.56 ’N	5340	857	167321.14
Rongxer Qu_B_17	86°12.22 ’E	28°13.66 ’N	5450	399	44328.44
Rongxer Qu_B_18	86°12.35 ’E	28°13.46 ’N	5420	368	40069.23
Rongxer Qu_B_24	86°13.41 ’E	28°10.97 ’N	5190	445	52872.10
Rongxer Qu_B_46	86°19.28 ’E	28°14.77 ’N	5390	830	260082.20
Rongxer Qu_B_7	86°9.02 ’E	28°14.96 ’N	5340	528	122856.17
Rongxer Qu_C_28	86°21.79 ’E	28°14.41 ’N	5350	1067	242590.27
Rongxer Qu_C_39	86°31.81 ’E	28°11.14 ’N	5050	1830	557639.97
Rongxer Qu_C_43	86°31.63 ’E	28°8.22 ’N	5110	2133	793293.47
Rongxer Qu_C_55	86°30.85 ’E	28°2.72 ’N	5240	1316	533354.06
Rongxer Qu_C_57	86°29.80 ’E	28°2.00 ’N	5080	954	320532.64
Rongxer Qu_C_67	86°26.17 ’E	27°56.21 ’N	5100	687	114723.70
Rongxer Qu_C_68	86°26.75 ’E	27°56.68 ’N	5170	1175	652607.20
Rongxer Qu_C_69	86°27.01 ’E	27°56.99 ’N	5100	300	50855.56
Rongxer Qu_C_71	86°26.09 ’E	27°55.74 ’N	5100	1013	322636.54

Chapter 12

Glacial Lake Outburst Flood Mitigation Measures, Monitoring and Early Warning Systems

There are several possible methods for mitigating the impact of Glacial Lake Outburst Flood (GLOF) surges, for monitoring, and for early warning systems. The most important mitigation measure for reducing GLOF risk is to reduce the volume of water in the lake in order to reduce the peak surge discharge.

Downstream in the GLOF prone area, measures should be taken to protect infrastructure against the destructive forces of the GLOF surge. There should be monitoring systems prior to, during, and after construction of infrastructures and settlements in the downstream area.

Careful evaluation by detailed studies of the lake, mother glaciers, damming materials, and the surrounding conditions are essential in choosing an appropriate method and in starting any mitigation measure. Any measure taken must be such that it should not create or increase the risk of a GLOF during and after the mitigation measures are in place. Physical monitoring systems of the dam, lake, mother glacier, and surroundings are necessary at different stages during and after the mitigation process.

12.1 REDUCING THE VOLUME OF LAKE WATER

Possible peak surge discharge from a GLOF could be reduced by reducing the volume of water in the lake. In general any one or combination of the following methods may be applied for reducing the volume of water in the lake:

- controlled breaching,
- construction of an outlet control structure,
- pumping or siphoning out the water from the lake, and
- making a tunnel through the moraine barrier or under an ice dam.

Controlled breaching

Controlled breaching is carried out by blasting, excavation, or even by dropping bombs from an aircraft. One of the successful examples has been that reported for Bogatyr Lake in Alatau, Kazakhastan (Nurkadilov et al. 1986). An outflow channel was excavated using explosives and 7 million cubic metres of water was successfully released in a period of two days. These methods, however, can give strong, uncontrolled regressive erosion of the moraine wall causing a fast lowering of the lake level. Lliboutry et al. (1977a, b, c) described a case from Peru of the sudden discharge of 6–10 million cubic metres of water after two years of careful cutting of a trench in he moraine wall.

Construction of an outlet control structure

For more permanent and precise control of lake outflows, rigid structures made out of stone, concrete, or steel can be used. However, the construction and repairs of the required mitigation works at high elevations, in difficult terrain conditions and in glacial lake areas far from road points and not easily accessed, will cause logistic difficulties. Therefore, preference should be given to construction materials available locally such as boulders and stones. The boulders on the moraine walls can be held in place by wire mesh ('gabion') and/or held down by appropriate anchors.

Open cuts in a moraine dam can be excavated during the dry season when a lake's water level is lower than during the wet season. Such a method is risky as any displacement wave arising from an ice avalanche can rip through the cut and breach the moraine. This method should be attempted where there is no risk of avalanches into the lake.

Pumping or siphoning the water out from the lake

Examples given by Lliboutry et al. (1977a, b, c) from Peru and the pumping programme for the control of Spirit Lake after the eruption of Mount St Helens in Washington State in the USA are very costly because of the large amount of electricity needed for the powerful pumps. The pumping facility consisted of 20 pumps with a total capacity of 5 $m^3 s^{-1}$ and the cost of the pumping plant, operation, and maintenance for about 30 months was approximately US $11 million (Sager and Chambers 1986).

In the Himalayan region, there is no hydroelectric power distribution system at high altitudes, nor a simple means of transporting fuel to high elevations. Many of the lakes are higher than the maximum flying altitude for helicopters.

The use of a turbine, propelled by the water force at the outside of the moraine dam, will lower the energy costs. The problems, of coupling the turbine and the pumps have to be solved.

Siphons with manageable component size are attractive in that they are readily transportable, relatively easy to install, and can be very effective for smaller size lakes.

Making a tunnel through the moraine dam

Tunnelling through moraines or debris barriers, although risky and difficult because of the type of material blocking the lake, has been carried out in several countries. In Peru, Lliboutry et al. (1977a, b, c) reported problems related to tunnelling through a moraine dam, which had been severely affected by an earthquake.

Tunnelling can only be carried out through competent rock beneath or beside a moraine dam. The costs of such a method are very high. Unfortunately, not all moraine dams are suitable for tunnelling.

The construction of tunnels would pose difficulties in the Himalayas due to the high cost of transporting construction materials and equipment to high elevations.

12.2 PREVENTATIVE MEASURES AROUND THE LAKE AREA

Any existing and potential source of a larger snow and ice avalanche, slide, or rockfall around the lake area, which has a direct impact on the lake and dam, has to be studied in detail. Preventative measures have to be taken such as removing masses of loose rocks to ensure there will be no avalanches into the lake.

12.3 PROTECTING INFRASTRUCTURE AGAINST THE DESTRUCTIVE FORCES OF THE SURGE

The sudden hydrostatic and dynamic forces generated by a rapid moving shock wave can be difficult to accommodate by conventionally designed river structures such as diversion weirs, intakes, bridges, settlements on the river banks, and so on. It will be necessary to build bridges with appropriate flow capacities and spans at elevations higher than those expected under GLOF events. The Nepal–China highway, after reconstruction, has arched bridges well above the 1981 GLOF levels. Also, the road has been moved to higher levels and has gabion protection at the base of the embankments. Settlements should not be built at or near low river terraces but at heights well above the riverbed in an area with GLOF potential. Slopes with potential or old landslides and scree slopes on the banks of the river near settlements should be stabilised. It is essential that appropriate warning devices for GLOF events be developed in such areas.

12.4 MONITORING AND EARLY WARNING SYSTEMS

A programme of monitoring GLOFs throughout the country should be implemented using a multi-stage approach, multi-temporal data sets, and multi-disciplinary professionals. Focus should first be on the known potentially dangerous lakes and the river systems on which infrastructure is developed. Monitoring, mitigation, and early warning system programmes could involve several phases as follow.

- Detailed inventory and development of a spatial and attribute digital database of the glaciers and glacial lakes using reliable medium- to large-scale (1:50,000 to 1:10,000) topographic maps
- Updating of the inventory of glaciers and glacial lakes and identification of potentially dangerous lakes using remote-sensing data such as ASTER images, the Land Observation Satellite (LANDSAT) Thematic Mapper (TM), Indian Remote Sensing Satellite (IRS)1C/D Linear Imaging and Self Scanning Sensor (LISS)3, Système Probatoire d'Observation de la Terre (SPOT) multi-spectral (XS), SPOT panchromatic (PAN) (stereo), and IRS1C/D PAN (stereo) images.
- Semi-detailed to detailed study of the glacial lakes, identification of potentially dangerous lakes and the possible mechanism of a GLOF using aerial photos.
- Annual examination of medium- to high-resolution satellite images, e.g. LANDSAT TM/ETM, ASTER, IRS1D, SPOT, and so on to assess changes in the different parameters of potentially dangerous lakes and the surrounding terrain
- Brief over-flight reconnaissance with small format cameras to view the lakes of concern more closely and to assess their potential for bursting in the near future
- Field reconnaissance to establish clearly the potential for bursting and to evaluate the need for preventative action
- Detailed studies of the potentially dangerous lakes by multi-disciplinary professionals
- Implementation of appropriate mitigation measure(s) in the highly potentially dangerous lakes
- Regular monitoring of the site during and after the appropriate mitigation measure(s) have been carried out
- Development of a telecommunication and radio broadcasting system integrated with on-site installed hydro meteorological, geophysical, and other necessary instruments at lakes of concern and downstream as early warning mechanisms for minimizing the impact of a GLOF
- Interaction/cooperation among all of the related government departments/institutions/agencies /broadcasting media, and others for detailed studies, mitigation activities, and preparedness for possible disasters arising from GLOF events.

Chapter 13

Conclusions

Databases of the glaciers and glacial lakes of Himalayan-China Region, based on medium- to large-scale topographic maps, have not been developed prior to the present study. For the glacier inventory the study used the methodology developed by the Temporary Technical Secretary for the World Glacier Inventory (Muller et al. 1977), and for the glacial lake inventory, the methodology developed by the Lanzhou Institute of Glaciology and Geocryology (LIGG) (LIGG/Water and Energy Commission Secretariat (WECS)/Nepal Electricity Authority [NEA] 1988) was used with modification. The present methodology for the compilation of inventories of glaciers and glacial lakes of Himalayan-China Region is applied using medium-scale maps.

The topographic maps based on aerial photographs and field verification, in the 1960s–1980s on a scale of 1:50,000 are the only map series that cover the whole of Himalayan-China Region on a medium scale. Based on this map series, spatial and attribute databases of glaciers and glacial lakes were developed.

Creating inventories of and monitoring glaciers and glacial lakes can be done quickly and correctly using a combination of satellite images simultaneously with topographic maps. The multi-stage approach of using remotely-sensed data and field data increases the ability and accuracy of the work. The integration of visual and digital image analysis with a geographic information system (GIS) can provide very useful tools for the study of glaciers, glacial lakes, and Glacial Lake Outburst Floods (GLOFs).

Analysts' experiences and adequate field knowledge of the physical characteristics of the glacier and lake and their associated features are always necessary for the interpretation of the topographic maps, and satellite images. Evaluation of spectral responses by different surface cover types in different bands of satellite images is necessary. Different techniques of digital image enhancement and spectral classification of ground features are useful for the study of glaciers and lakes. Different spectral band combinations in False Colour Composite (FCC) and individual spectral bands were used to study glaciers and glacial lakes using knowledge of image interpretation keys.

The Digital Elevation Model (DEM) is useful to decide the rules for discrimination of features and land-cover types in GIS techniques and for better perspective viewing and presentations. A DEM suitable for the present study of the whole country has been available. In this study, the DEM has played a key role not only to inventory the glaciers and glacial lakes, but to identify the potentially dangerous lakes. We propose that the DEM should been used in the further inventory of glaciers and glacial lakes.

The inventory of glaciers and glacial lakes of Himalayan-China Region as a whole is divided into eight basins, namely, the Jiazhagangge, Daoliqu, Majiacangbu, Jilongcangbu, Poiqu, Pumqu, Rongxer Qu, and Zangbuqin basin. Altogether 77 potentially danger lakes were identified in this study.

The characteristic features of the identified potentially dangerous lakes in general are:

- moraine-dammed glacial lakes in contact or very near to large glaciers,
- merging of supraglacial lakes at the glacier tongue,
- some new lakes of considerable size formed at glacier tongues,
- lakes rapidly growing in size
- rejuvenation of lakes after a past glacial lake outburst event.

There are several possible methods for mitigating the impact of GLOF surge, for monitoring, and for early warning systems. Careful evaluation by detailed studies of lakes, mother glaciers, damming materials, and the surrounding conditions are essential in choosing the appropriate method and in starting mitigation measures.

Summary of Glaciers and Glacial Lakes of Pumqu River Basin

S.N.	Sub basins Name	Glaciers		Glacial Lakes	
		Number	Area (km^2)	Number	Area (km^2)
1	**Pumqu**	716	1408.15	383	52.01
2	**Rongxer**	205	301.22	183	8.40
3	**Poiqu**	127	230.52	91	15.66
4	**Zangbuqin**	64	85.75	5	0.18
5	**Jilongcangbu**	180	418.61	72	3.32
6	**Majiacangbu**	147	216.16	69	4.73
7	**Daoliqu**	43	60.60	7	0.38
8	**Jiazhagangge**	96	143.30	14	0.52
Total		**1578**	**2864.33**	**824**	**85.19**

References

Ageta, Y.; Kadota, T. (1992) 'Predictions of Changes of Glacier Mass Balance in the Nepal Himalaya and Tibetan Plateau: A Case Study of Air Temperature Increase for Three Glaciers'. In *Annals of Glaciology*, 16: 89–94

Ageta, Y.; Ohata, T.; Tanaka, Y.; Ikegami, K; Higuchi, K. (1980) 'Mass and Heat Balances of the Glacier AX010, Shorong Himal during the Summer Monsoon Season, East Nepal'. In *Seppyo, Journal of the Japanese Society of Snow and Ice,* 41: 34–41 (special issue)

Alford, D. (1992) *Hydrological Aspects of the Himalayan Region*. Kathmandu, Nepal: ICIMOD

Arnoff, S. (1989) *Geographic Information Systems: A Management Perspective.* Ottawa, Canada: WDL

BC Hydro (1998) *Final Project Completion Report. Tsho Rolpa GLOF Warning System Project*

Benn, D.I.; Evans, D.J.A. (1998) *Glaciers and Glaciation*. London: Arnold

Bhusal, J.K. (1998) *Sediment Transport on Major Rivers in Nepal*. Paper presented at the International Workshop on Aspects and Impacts of Changing Sediment Regime, 16–20 1998, Asian Institute of Technology (AIT), Bangkok, Thailand

Bhusal, J.K. (1999) *Renewable Surface Waters of Nepal, Uses and Constraints to 21st Century*. Paper presented at the Third National Conference on Science and Technology, RONAST, Kathmandu, Nepal

Braun, M.; Fiener, P. (1995) *Report on the GLOF Hazard Mapping in the Imja Khola/Dudh Koshi Valley, Nepal,* Contribution to the Project 'Establishment of a Measure Service for Snow and Glacier Hydrology in Nepal'. Nepal: Snow and Glacier Hydrology Project, Department of Hydrology and Meteorology, HMG/N

Budhathoki, K.P.; Dongol, B.K.; Devkota, L.P.; Dhital, N.P.; Joshi, S.R.; Maskey, P.R.; (Damen, M.C.J.; van Westen, C.J., supervisors) (1996) *Aerospace Survey and GIS for GLOF Hazard Zonation, Rolwaling and Tama Koshi Valleys, Dolakha District, Nepal*, Field Work Report submitted as a Partial Requirement of the Special Postgraduate Diploma Course on 'Mountain Hazard Zonation in the Himalayas, with Emphasis on GLOF' (5 September 5 1995–4 July 4 1996) to the ITC, The Netherlands

Carson, B. (1985) *Erosion and Sedimentation Processes in the Nepalese Himalaya*, Occasional Paper No. 1. Kathmandu: ICIMOD

CBS (1999) *Statistical Year Book of Nepal*

Chaohai, Liu; Liangfu, Ding (1986) 'The Newly Progress of Glacier Inventory in Tianshan Mountains'. In *Journal of Glaciology and Geocryology*, 8(2): 168–169

Chikita, K.; Yamada, T.; Sakai A.; Ghimire, R.P. (1997) 'Hydrodynamic Effects on the Basin Expansion of Tsho Rolpa Glacier Lake in the Nepal Himalaya'. In *Bulletin of Glacier Research* (Data Center for Glacier Research, Japanese Society of Snow and Ice), Publication No. 15: 59–69

Clague, J.J.; Mathews, W.H. (1973) 'The Magnitude of Jokulhlaups'. In *Journal of Glaciology*, 12(66): 000–000

Costa, J.E. (1985) *Floods from Dam Failures*, Open File Report. USA: US Geological Survey

Costa, J.E. (1988) 'Floods from Dam Failures'. In Baker, V.R.; Kochel, R.G.; Patton, P.C. (eds) *Flood Geomorphology*, pp 439–463. New York: Wiley Interscience

Damen, M. (1992) *Study on the Potential Outburst Flooding of Tsho Rolpa Glacier Lake, Rolwaling Valley, East Nepal*. The Netherlands: Netherlands–Nepal Friendship Association, International Institute for Aerospace Survey and Earth Sciences, ITC

Department of Hydrology and Meteorology (1998) 'Hydrological Records of Nepal, Station No. 695'.

Desloges, J.R.; Jones, D.P.; Ricker, K.E. (1989) 'Estimates of Peak Discharge from the Drainage of Ice-dammed Ape Lake, British Columbia, Canada'. In *Journal of Glaciology*, 35: 349–354

DHM (1992) *Study on Nationwide Hydro-meteorological Data Management Project*, Interim Report No. 1. Department of Hydrology and Meteorology/Japan International Cooperation Agency (JICA)

DHM (1997a) *Snow and Glacier Hydrology Section Year Book 1995*, Supplement No. V. Nepal: Snow and Glacier Hydrology Section, Department of Hydrology and Meteorology, HMGN

DHM (1997b) *Thulagi Glacier Lake Study*, final report. Department of Hydrology and Meteorology, HMG/N in cooperation with Federal Institute for Geo-sciences and Natural Resources (BGR), Hannover, Germany

DHM (1997c) *Tsho Rolpa GLOF Risk Reduction Project*, Formulation Mission Final Report

DHM (1998a) *Hydrological Records of Nepal. Streamflow Summary*. Nepal: DHM, HMG/N

DHM (1998b) *Tsho Rolpa GLOF Risk Reduction Project*, Implementation Report

DHM (1999a) *Climatological Records of Nepal. 1995–1996*. Nepal: DHM, HMGN

DHM (1999b) *Daily Precipitation Record of Gandaki and Narayani Zone through 1996*. Nepal: DHM, HMGN

DHM (2000) *Tsho Rolpa Glof Risk Reduction Project*, Design Build and Project Management Contracts, Quarterly Progress Report No. 5

Dwivedi, S.K.; Acharya, M.D.; Joshi, S. P. (1999) 'Preliminary Report on the Tam Pokhari GLOF of 3rd September 1998'. In *WECS Bulletin*, 10(1): 11–13

Electricity Development Center (1994) Detailed Project Report (DPR) Pancheshwar Multipurpose Project.

Electrowatt Engineering Service Ltd (1982) *Feasibility Study of Mulghat Hydropower Project*, Report to Asian Development Bank and HMG/N

Electrowatt Engineering Services Ltd. (1982) Feasibility study of Mulghat Hydropower project; Report to Asian Development Bank and HMG Nepal.

ESCAP (1993) ‘Geology and Mineral Resources of Nepal’. In *Atlas of Mineral Resources of the ESCAP Region*, Vol 9. Economic and Social Commission for Asia and the Pacific in cooperation with the Department of Mines and Geology, Ministry of Industry, HMG/N.

Fukushima, Y.; Watomabe, O.; Higuchi, K. (1991) ‘Estimation of Stream-flow Change by Global Warming in a Glacier-covered High Mountain Area of Nepal Himalaya’. In *Internal Associate of Hydrological Sciences Publication*, 205 (Symposium at Vienna 1991—Snow Hydrology and Forests in High Alpine Areas): 181–188

Fushimi, H. (1977) ‘Glaciations in the Khumbu Himal (1)’. In *Seppyo, Journal of the Japanese Society of Snow and Ice*, 39(2): 60–67 (special issue)

Fushimi, H. (1978) ‘Glaciations in the Khumbu Himal (2)’. In *Seppyo, Journal of the Japanese Society of Snow and Ice*, 40(3): 71–77 (special issue)

Fushimi, H.; Ikegami, K.; Higuchi, K.; Shankar, K. (1985) ‘Nepal Case Study; Catastrophic Floods’. In *AHS Publication*, 149: 125–130

Fushimi, H.; Ohata, T. (1980) ‘Fluctuations of Glaciers from 1970 to 1978 in the Khumbu Himal’. In *Seppyo, Journal of the Japanese Society of Snow and Ice*, 41(4): 67–70 (special issue)

Fushimi, H.; Yaunari, T.; Higuchi, H.; Nagoshi, A.; Watanabe, O.; Ikegami, K.; Higuchi, K.; Ageta, Y.; Ohata, T.; Nakajima, C. (1980) ‘Preliminary Report on Flight Observations of 1976 and 1978 in the Nepal Himalayas’. *Seppyo, Journal of the Japanese Society of Snow and Ice*, 41(4): 62–66 (special issue)

Galey, V.J. (1985) *Glacier Lake Outburst Flood on the Bhote/Dudh Koshi, August 4, 1985*, WECS internal report. Kathmandu: WECS

Government of India (GOI) (1981) *Feasibility Report of Koshi High Dam Project.* 3-23.

Grabs, W.E.; Pokhrel, A.P. (1992) ‘Establishment of Measuring Service for Snow and Glacier Hydrology in Nepal—Conceptual and Operational Aspects’. In Young, G.J. (ed.) *International Symposium on Snow and Glacier Hydrology*, pp 3–16. Kathmandu: IAHS

Hammond, J.E. (1988) *Glacial Lake in the Khumbu Region, Nepal: An Assessment of the Hazards*. MA Thesis. Boulder, USA: Department of Geology, University of Colorado

Hanisch, J.; Delisle, G.; Pokhrel, A.P.; Dixit, A.M.; Reynolds, J.M.; Grabs, W.E. (1998) ‘The Thulagi Glacier Lake, Manasulu Himal, Nepal—Hazard Assessment of a Potential Outburst’. In Moore, D.; Hungr, O. (eds) *Proceedings of Eighth International Congress International Association for Engineering Geology and the Environment, 21–25 September 1998, Vancouver, Canada*, pp 2209–2215

Hansen, J.; Ruedy, R.; Sato, R.; Reynolds, R. (1996) ‘Global Surface Air Temperature in 1995: Return to Pre-Pinatubo Level’. *Geophysical Research Letters*, 23: 1665–1668

Hewitt, K. (1985) *Pakistan Case Study: Catastrophic Floods*, Publication No. 149. UK: IAHS

Higuchi, K.; Fushimi, H.; Ohatga, T.; Iwata, S.; Yokoyama, K.; Higuchi, H.; Nagoshi, A.; Iozawa, T. (1978) ‘Preliminary Report on Glacier Inventory in the Dudh Koshi Region’. *Seppyo, Journal of the Japanese Society of Snow and Ice*, 40: 71–77 (special issue)

Himal Power Consultants and Karnali (Chisapani) Multipurpose Project (1989) Feasibility Study (Main Report) Submitted to Ministry of Water Resources, HMG Nepal, 11-1 to 11-7.

Himalayan Power Consultants (1989) Karnali (Chisapani) Multipurpose Project, Annex E, Sedimentation, 1-2

Ives, J.D. (1986) *Glacial Lake Outburst Floods and Risk Engineering in the Himalaya*, Occasional Paper No. 5. Kathmandu: ICIMOD

Iwata, S. (1976) 'Late Pleistocene and Holocene Moraines in the Sagarmatha(Everest) Region, Khumbu Himal'. In Seppyo, Journal of the Japanese Society of Snow and Ice, 38: 109–114 (special issue)

JICA (1983) 'Feasibility Report on Sapta Gandaki Hydroelectric Power Development Project'. Submitted to HMG Nepal Vol. 1 (4 –13) and Vol II (c-19 to c-22)

JICA (1985) 'Master Plan Study on the Koshi River Water Resources Development'. Submitted to HMG Nepal, Vol. I and Vol. II

JICA (1987) Draft Final Report on Feasibility Study on Arun 3 – Hydro-Electric Power Development Project Vol. I Main Report, 5 – 43.

Kadota, T.; Ageta, Y. (1992) 'On the Relation between Climate and Retreat of Glacier AX010 in the Nepal Himalaya from 1978 to 1989'. In *Bulletin of Glacier Research*, 10: 1–10

Kettelmann, R.; Watanabe, T. (1998) 'Approaches to Reducing the Hazard of an Outburst Flood of Imja Glacier Lake, Khumbu Himal'. In Chalise, S.R.; Khanal, N.R. (eds) *Proceeding of the International Conference on Ecohydrology of High Mountain Areas, Kathmandu, Nepal, 24-28 March 1996*, pp 359–366. Kathmandu: ICIMOD

Kodama, H.; Mae, S. (1976) 'The Flow of Glaciers in the Khumbu Region'. *Seppyo, Journal of the Japanese Society of Snow and Ice*, 38: 31–36 (special issue)

Kraus, H. (1988) *The Climate of Nepal, Studies on the Climatology and Phytogeology of the Himalaya: Selections from Khumbu Himal*. Kathmandu: Nepal Research Centre

Liboutry, L.; Arnoa, B.M.; Schnieder, B. (1977a) 'Glaciological Problems set by the Control of Dangerous Lake in Cordillera Blanca, Peru; Part I; Historical Failures of Morainic Dams, their Causes and Prevention'. In *Journal of Glaciology*, 18(79): 000–000

Liboutry, L.; Arnoa, B.M.; Schnieder, B. (1977b) 'Glaciological Problems set by the Control of Dangerous Lake in Cordillera Blanca, Peru; Part II; Movement of a Covered Glacier Embedded within a Rock Glacier'. In *Journal of Glaciology*, 18(79): 000–000

Liboutry, L.; Arnoa, B.M.; Schnieder, B. (1977c) 'Glaciological Problems set by the Control of Dangerous Lake in Cordillera Blanca, Peru; Part III; Studies of Moraines and Mass Balances at Safund'. In *Journal of Glaciology*, 18(79): 000–000

LIGG/WECS/NEA (1988) *Report on First Expedition to Glaciers and Glacier Lakes in the Pumqu (Arun) and Poique (Bhote-Sun Koshi) river basins, Xizang (Tibet), China, Sino-Nepalese Investigation of Glacier Lake Outburst Floods in the Himalaya*. Beijing, China: Science Press

Mae, S. (1976) 'Ice Temperature of Khumbu Glacier'. In *Seppyo, Journal of the Japanese Society of Snow and Ice*, 38: 37–38 (special issue)

Marcus, M.G. (1960) 'Periodic Drainage of Glacier-dammed Tulsequah Lake, B.C.'. In *Geographical Review*, 31: 000–000

Modder S.; van Olden, Q. (1995) *Geotechnical Hazard Analysis of a Natural Moraine Dam in Nepal*, Interim Report. The Netherlands: Free University of Amsterdam

Modder S.; van Olden, Q. (1996) *Engineering—Geomorphological Analyis of Moraine Dam in the Nepal Himalayas, A detail survey (scale 1:1500) at Tsho Rolpa Glacier Lake, Rolwaling Valley, Dholakha District, East Nepal*, Part 1: text. MSc Thesis. The Netherlands: Faculty of Earth Sciences, Vrije Universiteit Amsterdam

Modder S.; van Olden, Q. (1996) *Engineering—Geomorphological Analyis of Moraine Dam in the Nepal Himalayas, A detail survey (scale 1:1500) at Tsho Rolpa Glacier Lake, Rolwaling Valley, Dholakha District, East Nepal*, Part 2: appendices. MSc Thesis. The Netherlands: Faculty of Earth Sciences, Vrije Universiteit Amsterdam

Modder S.; van Olden, Q. (1996) *Preliminary Presentation of Geotechnical Data and Maps (separate) of The Tsho Rolpa End Moraine Complex*. The Netherlands: Vrije Universiteit Amsterdam

Mool, P.K. (1995a) 'Glacier Lake Outburst Floods in Nepal'. In *Journal of Nepal Geological Society,* 11: 273–280 (special issue)

Mool, P.K. (1995b) *Monitoring of Land Cover of Glaciated Mountain Environment, Rolwaling—Sagarmatha (Everest) Area, Nepal, using* Remote sensing *(ERDAS IMAGINE) and GIS Technique*, report on JICA Counter Part Training. Tokyo, Japan: PASCO Corporation

Mool, P.K. (1998) 'Use of Multi-Temporal Data for the Study of Glacier Lakes and Glacier Lake Outburst Floods in Nepal Himalaya: Tsho Rolpa Glacier Lake as a Case Study'. In *Proceedings of International Symposium on Application of* Remote sensing *and Geographic Information System to Disaster Reduction, Tsukuba, Japan, 3 March 1998*, pp 13–21

MOPE (1998) *State of the Environment, Nepal*. Nepal: Ministry of Population and Environment, HMG/N

Morton (1983) 'Operational Estimates of Aerial evapo-transpiration and their Significance to the Science and Practice of Hydrology'. In *Journal of Hydrology,* 66: 1–76

Muller, F. (1959) *Eight Months of Glaciers and Soil Research in the Everest Region (The Mountain World 1958/59)*, pp 191–208. London: Allen & Unwin

Muller, F. (1980) *Present and Late Pleistocene Equilibrium Line Altitudes in the Mt. Everest Region—An Application of the Glacier Inventory,* Riederalp Workshop. IHAS-AISH

Muller, F.; Caflish, T.; Muller, G. (1977) *Instruction for Compilation and Assemblage of Data for a World Glacier Inventory*. Zurich: Temporary Technical Secretariat for World Glacier Inventory, Swiss Federal Institute of Technology, Zurich

Nakawo, M.; Fujita, K; Ageta, Y.; Shankar, K.; Pokhrel, A.P.; Yao, T. (1997) 'Basic Studies for Assessing the Impacts of the Global Warming on the Himalayan Cryosphere, 1994–1996. *Bulletin of Glacier Research*, 15: 53–58

Nayava, J.L. (1980) 'Rainfall in Nepal'. In *The Himalayan Review*, 12: 1–18

NEA (1995) *Report on the Field Trip to the Lower Barun Glacier Lake on 17/4/1995*. Arun III Hydroelectric Project, Detailed Engineering Services, Joint Venture Arun III Consulting Services, Lahmeyer International, Energy Engineering International, and Electric Power Development Company Ltd

Neda (2000) *Tsho Rolpa GLOF Mitigation Projects. Analysis of Micro-tunneling Option*

Nippon Koei Co. Ltd. Tokyo (1966) Hydroelectric Development of the Karnali River, Nepal Feasibility Report on the Chisapani High Dam Project, Report prepared for the United Nations Action as Executive Agency for the UNDP; Vol. II, 31-38.

NPC (1998) *Ninth Five Year Plan (1996/97–2001/02)*

Nurkadilov, L.K.; Khegai, A.U.; Popov, N.V. (1986) 'Artifical Draining of an Outburst-dangerous Lake at the Foot of Surging Glacier'. In *Data of Glaciological Studies*, 18: 220–221

Pancheshwar Multipurpose Project (1991) Field Investigation within Nepal Territory, Final Report Vol II – Site Investigation, Sediment Investigation; Pancheshwar Consortium, Section 10.

Pender, M. (1995) 'Recent Retreat of the Terminus of Rika Samba Glacier, Hidden Valley, Nepal'. In Wake, C.P. (ed.) *Himalayan Climate Expedition—Final Report*, pp 32–39. Durham, New Hampshire: Glacier Research Group, University of New Hampshire

Penman (1956) 'Evaporation and Introductory Survey'. In *Netherlands Journal of Agricultural Science*, 4: 9–29

Rana B.; Nakawo M.; Fukushima Y.; Ageta Y. (1997) Application of a conceptual precipitation-runoff model (HYCYMODEL) in a debris Langtans Valley, Nepal Himalaya. In *Annals of Glaciology*, 25: 226–231

Reynolds Geo-Sciences Ltd (1994) *Hazard Assessment at Tsho Rolpa, Rolwaling Himal, Northern Nepal*, Technical Report No: J9402.002 submitted to WECS. Kathmandu, Nepal

Röthlisberger, F.; Geyh, M.A. (1985) 'Glacier Variations in Himalayas and Karakorum'. In Zeitshrift für Gletscherkunde und Glazialgeologie, 21: 237–249

Sager, J.W.; Chambers, D.R. (1986) *Design and Construction of the Spirit Lake Outlet Tunnel, Mount St. Helens, Washington*, Special Geotechnical Publication No. 3. New York, USA: ASCE

Seko, K.; Takahashi, S. (1991) 'Characteristics of Winter Precipitation and its Effect on Glaciers in the Nepal Himalaya'. In *Bulletin of Glacier Research*, 9: 9–16

Shankar, K.; Shrestha P.B (1985b) 'Water Resources'. In Majupuria, T.C. (ed.) *Nepal—Nature's Paradise*, pp 25–32. Bangkok: White Lotus

Shankar, K.; Shrestha P.B. (1985a) 'Climate'. In Majupuria, T.C. (ed.) *Nepal—Nature's Paradise*, pp 39–44. Bangkok: White Lotus

Shiraiwa, T. (1993) *Glacier Fluctuations and Cryogenic Environments in the Langtang Valley, Nepal Himalaya*, contributions from the Institute of Low Temperature Science, Series No. 38. Sapporo: The Institute of Low Temperature Science, Hokkaido University

Shrestha, A.B.; Wake, C.P., Dibb, J.E. (2000) 'Precipitation Fluctuations in the Himalaya and its Vicinity: An Analysis Based on Temperature Records from Nepal'. In *International Journal of Climate*, 20: 317–327

Shrestha, A.B.; Wake, C.P.; Mayewski, P.A.; Dibb, J.E. (1999) 'Maximum Temperature Trends in the Himalaya and its Vicinity: An Analysis Based on Temperature Records from Nepal for the Period 1971–94.' In *Journal of Climate*, 12: 2775–2787

Shrestha, H.M. (1965) *Our Rivers—A Preliminary Study in Gokhaptra (Magh 23, 2022)*

Shrestha, H.M. (1966) *Cadastre of Hydropower Resources of Less-studied High Mountainous Regions (in the example of Nepal)*

Shrestha, H.M. (1968) 'Water Power Potential of Nepal (its Theoretical and Technical limitations)'. In *Transactions of VII World Power Conference*

Shrestha, H.M. (1985) 'Water Power Potential'. In Majupuria, T.C. (ed.) *Nepal—Nature's Paradise*, pp 32–38. Bangkok: White Lotus

Shrestha, H.M. (1995) *Hydropower in WECS*, Supporting Document No. 2, Energy Perspective Plan

Singh, I.L. (1985) 'Rainfall Distribution'. In Majupuria, T.C. (ed.) *Nepal—Nature's Paradise*, pp 56–58. Bangkok: White Lotus

Swain, P.H.; Davis S.M. (eds) (1979) Remote sensing*: The Quantitative Approach*. USA: McGraw-Hill

Tanaka, Y.; Ageta, Y.; Higuchi, K. (1980) 'Ice Temperature Near the Surface of Glacier AX010 in Shorong Himal, East Nepal'.In *Seppyo, Journal of the Japanese Society of Snow and Ice,* 41(4): 55–61 (special issue)

Thornthwaite, C.W. (1948) 'An Approach Towards Rational Classification of Climate'. In: *Geographical Review*, 38: 55–94

Vuichard, D.; Zimmerman, M. (1986) 'The Langmoche Flash Flood, Khumbu Himal, Nepal'. In *Mountain Research and Development*, 6(1): 90–94

Vuichard, D.; Zimmerman, M. (1987) 'The 1985 catastrophic drainage of a moraine-dammed lake, Khumbu Himal, Nepal: Cause and consequence'. In *Mountain Research and Development*, 7(2): 91–110

Watanabe, O. (1976) 'On the Types of Glaciers in the Nepal Himalayas and Their Characteristics'. In *SEPPYO*, 38, 10-16

Watanabe, T.; Ives, J.D.; Hammond, J.E. (1994) 'Rapid Growth of a Glacial Lake in Khumbu Himal, Himalaya: Prospects for a Catastrophic Flood'. In *Mountain Research and Development*, 14(4): 329–340.

Watanabe, T.; Kameyama, S.; Sato, T. (1995) 'Imja Glacier Dead-Ice Melt Rates and Changes in a Supra-glacial Lake, 1989-1994, Khumbu Himal, Nepal: Danger of Lake Drainage'. In *Mountain Research and Development*, 15(4): 293–300

Wavin Overseas B.V. (1996) *Trial Siphon at Lake Tso Rolpa*, Report on Siphon Installation (Tsho Rolpa/JVN), submitted to WECS, Kathmandu, Nepal

WECS (1987a) *Erosion and Sedimentation in the Nepal Himalaya; an Assessment of River Process*, WECS Report No. 4/3/010587/1/1, Seq. No. 259. Kathmandu, Nepal: WECS

WECS (1987b) *Study of Glacier Lake Outburst Floods in the Nepal Himalayas, Phase I, Interim Report, May, 1997*, WECS Report No. 4/1/200587/1/1, Seq. No. 251. Kathmandu, Nepal: WECS

WECS (1991) *Preliminary Work Report on Glacier Lake Outburst Flood in the Nepal Himalayas*, WECS Report No. 4/1/291191/1, Seq. No.387. Kathmandu, Nepal: WECS/JICA

WECS (1993a) *Interim Report on the Field Investigation on the Tsho Rolpa Glacier Lake, Rolwaling Valley*, WECS Report No. 3/4/021193/1/1, Seq. No. 436. Kathmandu, Nepal: WECS

WECS (1993b) *Preliminary Report on the First Field Investigation on the Lower Barun Glacier Lake*, WECS Report No. 3/4/080893/1/1 Seq. No.428. Kathmandu, Nepal: GLOF Unit, WECS

WECS (1994) *Report for the Field Investigation on the Tsho Rolpa Galcier, Rolwaling Valley, February 1993–June 1994*, WECS N551.489 KAD. Kathmandu, Nepal: WECS

WECS (1995a) *Data Report, Meteorological and Hydrological Data at Tsho Rolpa Glacier Lake, Rowaling Himal—From June 1993 to May 1995*, WECS N551489 DAT. Kathmandu, Nepal: WECS

WECS (1995b) *Electrical Resistively Exploration at Tsho Rolpa End Moraine*, WECS N551.489 OYO. Kathmandu, Nepal: WECS

WECS (1995c) *Preliminary Report on the Thulagi Glacier Lake, Dhana Khola, Marsyangdi Basin*, WECS Report No. 473, Seq. No. 2/3/170795/1/1. Kathmandu, Nepal: WECS

WECS (1995d) *Report on Tsho Rolpa Glacier Lake Field Visit in Rolwaling Himal—Post-monsoon Season, 1995*, WECS N551.489 WAT. Kathmandu, Nepal: WECS

WECS (1995e) *The Debris Flow and the Hazard due to GLOF in the Rolwaling Valley, Nepal,* WECS N551.489 FUJ. Kathmandu, Nepal: WECS

WECS (1996) *Report on the Investigations of Tsho Rolpa Glacier Lake, Rolwaling Valley*. WECS/JICA

WECS (1997) *Study and Topographic Mapping of Lower Barun Glacier Lake*, Vol 1. Kathmandu, Nepal: WECS

WECS (1999) 'Nepal Energy Supply Demand Balance'. In *WECS Bulletin*, 10(1/2): 000–000

WGMS (1989) *World Glacier Inventory, Status 1988,* a contribution to the Global Environment Monitoring System (GEMS) and the International Hydrological Programme, compiled by the World Glacier Monitoring Service (WGMS). IAHS (ICSI), UNEP, UNESCO

WGMS (1998) Fluctuations of Glaciers, 1990–1995, Vol. VII, a contribution to the Global Environment Monitoring System (GEMS) and the International Hydrological Programme; compiled by the World Glacier Monitoring Service (WGMS). IAHS (ICSI), UNEP, UNESCO

Williams, G.P. (1988) 'Paleofluvial Estimates from Dimensions of Former Channels and Menders'. In Baker,V.R; Kochel, R.C.; Patton, P.C. (eds) *Flood Geomorphology*, pp 321–334. New York: Wiley Interscience

Williams, V.S. (1983) 'Present and Former Equilibrium Line Altitudes near Mount Everest, Nepal and Tibet'. In *Arctic and Alpine Research*, 15: 201–211

XuDaoming (1985) *Characteristics of Debris Flows Caused by Outbursts of Glacier Lakes in Boqu River in Xizang, China, 1981*. Lanzhou Institute of Glaciology and Cryopedology, Academia Sinica

Yamada, T. (1992) *Report for the First Research Expedition to Imja Glacier Lake – 25 March to 12 April 1992*, WECS Report No. 3/4/120892/1/1, Seq. No. 412. Kathmandu, Nepal: WECS/JICA

Yamada, T. (1993) *Glacier Lakes and their Outburst Floods in the Nepal Himalaya*. Kathmandu, Nepal: WECS

Yamada, T. (1998) *Glacier Lake and its Outburst Flood in the Nepal Himalaya*. Data Center for Glacier Research, Japanese Society of Snow and Ice

Yamada, T.; Shiraiwa, T.; Iida, H.; Kadota, T.; Watanabe, T.; Rana, B.; Ageta, Y.; Fushimi, H. (1992) 'Fluctuations of the Glaciers from the 1970s to 1989 in the Khumbu, Shorong and Langtang Regions, Nepal Himalayas'. In *Bulletin of Glacier Research*, 10: 11–19

Zimmermann, M.; Bichsel, M.; Kienholz, H. (1986) 'Mountain Hazards Mapping in the Khumbu Himal, Nepal, with prototype map, scale 1:50,000'. In *Mountain Research and Development*, 6(1): 29–40