IMPACT OF CLIMATE CHANGE ON GLACIERS: A CASE STUDY OF LUNANA REGION IN BHUTAN

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

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in

IRRIGATION WATER MANAGEMENT

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By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the *Dissertation* entitled" **IMPACT OF CLIMATE CHANGE ON GLACIERS: A CASE STUDY OF LUNANA REGION IN BHUTAN"** in the partial fulfillment of the requirement for the award of degree of **Master in Technology** in **Irrigation Water Management** and submitted in the Department of Water Resource Development and Management of Indian Institute of Technology Roorkee is a record of my own work carried out during a period from July 2010 to June 2011 under the excellent supervision of **Dr. Deepak Khare**, Professor in the Department Of Water Resource Development and Management, Indian Institute of Technology Roorkee, INDIA.

The matter embodied in this *Dissertation* has not been submitted by me for the award of any other degree.

Roorkee
June, 28/2011

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This is to certify that the above mentioned statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

In the northern region of Bhutan, supra glacial ponds on some debris-covered glaciers in the 1950s have subsequently grown into moraine-dammed lakes. Also, pro-glacial lakes have expanded substantially as a result of retreat of glacier termini. Study discussed the evolution of these lakes in detail using maps, photographs, and satellite images.

This explains about the climate change of Bhutan for last 15 years up till now and how it affects on the Glaciers on mountainous regions. It also tells about the formations of Glaciers and retreating rate of the Glaciers at the moment and the expansions of different Glacial lakes of Bhutan especially in Lunana region, and risk associated from potential of Glacier Lake Outburst Flood in low lying area and types of mitigations that are possibly can be provided. On top of that, it also explains the affects of climate change on glaciers and glacial lakes annually as well as seasonally have been observed.

Firstly, the statistical methods were used to determine temporal trends and their spatial distribution of historical annual and seasonal precipitation and temperature series for the period of fifteen years. The method used for this, is Mann Kendall (MK), Non-parametric tests searches for detecting and assessing significant trend in climate time series, without specifying whether trend is linear or non-linear. The true slope (change per unit time) is estimated by using non-parametric procedure developed by Sen's slope (Q) Method.

Secondly, the study stresses the importances of Methodologies were used for the assessment of Glacier retreat rate, expansion of Glacial Lakes rate. Assessment of Glaciers retreat and expansion of Glacial Lakes are being determined by using AcrGIS 9.3. The land use of whole watershed delineation area has been done using ERDAS imagine by observing the changes of glaciers and glacial lakes with time. Here the data were of four different years of Landsat images of 1990, 2001, 2007 and2009 and also the spot images of 2009 of which they are from almost the same months.

Thirdly, the unsteady analysis of River (Pochu) by using the HEC-RAS 4.0 and since it does not have adequate data, in present study it shows only the profile of river. Its cross-sections of the River were also been extracted from the HEC-GeoRAS in GIS due to the lack of surveyed data by using the SRTM (90m) on converting into TIN(triangulated integrated network).

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LIST OF ACRONYMS

ADB	Asian Development Bank
AOI	Area of Interest
ACIA	Arctic Climate Impact Assessment
CO_2	Carbon dioxide
CH_4	Methane
CFCs	Chlorofluorocarbon
CO	Carbon monoxide
CECS	Centro de Estudios Científicos
CSIRO	Common Wealth Scientific Research Organization.
CCSP	Climate Change Science Program
CRU	Climatology Research Unit
CGI	Comitato Glaciologico Italiano
DEM	Digital Elevation Model
EEA	European Environment Agency
ENEA	Ente per le Nuove tecnologie, l'Energia e l'Ambiente
FAO	Food Agriculture Organization
GPCP	Global Precipitation Climatology Project
GPCC	Global Precipitation Climatology Centre.
GHCN	Global Historical Climatology Network
GLIMS	Global Land Ice Measurements from Space
GIS	Geographical Information System
GNH	Gross National Happiness
GDP	Gross Domestic Products
GLOF	Glacial Lakes Outburst Flood
GHG	Green House Gas
GCOS	Global Climate Observing System
IPCC	Intergovernmental Panel on Climate Change
ICIMOD	International Centre for Integrated Mountain Development
LANDSAT	Land observation resources satellite.
LIA	Little Ice Age
INACH	Instituto Antártico Chileno
LIGG	Lanzhou Institute of Glaciology and Geocryology (in China)
MW	Mega Watts

m.a.s.l	mean above sea level
N_2O	Nitrous oxide
NEA	National Energy Action
NAPA	National Adaptation Program of Action
NEC	National Environment Commission
PM	Particulate Matter.
Pmm	Parts Per Million
PREC/L	Precipitation Reconstruction on Land.
SRTM	Shuttle Radar Transmission Mission
SPOT	System Probatoire Pour l' Observation de la terre/Satellite Poul'Observation de la Terre
SLE	Sea Level Equivalent
TIN	Triangulated Integrated network
TAR	Third Assessment Report
TEMPO	Telecommunication Modernization Project
TM	Thematic Mapper
UN	United Nations
WMO	World Meteorological Organization.
WECS	Water and Energy Commission Secretariat (Nepal)
WGI	Working Group I-IPCC
WGII	Working Group II-IPCC
WGMS	World Glacier Monitoring Service

LIST OF SYNONYMS

Chu	River/streams
Tshachhu	Hot springs
Menchhu	Hot stone bath
Drupchhu	Clean spring water
Dzongkhag	Districts
Ngalops	Western people of Bhutan
Sharchops	Eastern people of Bhutan
Lhotshampas	Southern people of Bhutan
Shangrila	Himalaya
Dzong	Fortress

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Bhutan is a mountainous country, where mountains and hills occupy most of the land. Out of the 2,400 km long Himalayan range, the Bhutan Himalayas extend up to 340 km. The country is vulnerable to various hazards due to fragile geological conditions, great elevation differences, and steep sloping terrain. Apart from landslides and river erosion, the mountainous region is also quite susceptible to disastrous hazards due to the glacial lakes outburst floods (GLOFs).In general, the area above an elevation of 4,000 masl is mostly covered by snow and ice throughout the year. The glaciers, some of which consist of a huge amount of perpetual snow and ice, create many glacial lakes. These glaciers, as well as the 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 accumulation of a huge amount of water from the melting of snow and ice cover and by blockage of end moraines. The sudden break of the moraine may generate a discharge of large volume of water and debris causing flooding.

In the last half- century, several glacial lakes have developed in the Hindus Kush-Himalayas and Tibetan Himalayas. This may be attributed to the effect of recent global warming. The glacial lakes are formed on the glacial terminus due to the recent retreating processes of the glaciers. The majority of these glacial lakes are dammed by unstable moraines, which were formed by the glaciations of the little Ice Age. Occasionally, the lakes happen to burst and suddenly release an enormous amount of its stored water, which causes serious floods downstream along the river channel. This phenomenon, generally known as glacial lakes outburst flood (GLOF), is recognized to be a common problem in Hindu Kush-Himalayan countries such as Nepal, India, Pakistan, Bhutan and China and even Afghanistan.

In Bhutan, the sources of its major rivers and the bulk of its fresh water resources are located up in ice and snow. The advance of glaciers during the Little Ice Age has built up prominent end moraines in the Higher Himalaya of Bhutan in the head waters of Pochu, Mochu etc. During the last few decades there has been a rapid retreat of glaciers creating many dangerous moraines-dammed lakes. in some glaciers(e:g Thormithormi) small isolated lakes/ponds have formed. They are increasing in size at a very fast rate. It has been observed that some of the glaciers in Bhutan are retreating at the rate of 20-30 m a year.

1.2 IMPORTANCE OF WATER RESOURCES

Water resources have been one of the most important areas of World. Therefore the following points are important that need the water resources.

For industry,extensive water conservation and protection of groundwater sources are necessary. Experience in industrial countries suggests that controlling pollution will also substantially reduce the quantity of water used per unit of industrial output.For water supply and sanitation, more efficient and accessible delivery of water services and sewage collection, treatment, and disposal, with the ultimate goal of providing universal coverage. This will be achieved by extending existing supplies through water conservation and reuse and by using other sustainable methods. Therefore greater involvement of the private sector, nongovernmental organizations, and user groups will be required.

For irrigation and hydropower, modernized irrigation practices, greater attention to cost recovery, drainage and salinity control, measures to reduce pollution from agricultural activities, improvements in operation and maintenance of existing systems, and investments in small-scale irrigation and various water-harvesting methods.This calls for the development of institutions and technologies that respond to the needs of farmers for higher-quality services, including greater participation of community groups and user associations, while reinforcing the efficient management of demand. Particular attention will be given to the needs of small-scale farmers, who comprise most of the agricultural community.

Greater priority should be given to managing the demand for energy, identifying small-scale and renewable energy alternatives, promoting watershed conservation practices, and retrofitting and enhancing dam facilities. For the environment and poverty alleviation, more rigorous attention to minimizing resettlement, maintaining biodiversity, and protecting ecosystems in the design and implementation of water projects. Water and energy supplies gained through conservation and improved efficiency can be used instead of developing new supplies to extend service to the poor and maintain water-dependent ecosystems. Low-cost and environmentally benign methods of developing new water supplies for agriculture, rural drinking water, and industry will be pursued.

The water supply needs of rivers, wet lands, and fisheries will be considered in decisions concerning the operation of reservoirs and the allocation of water.

1.3 AVAILABILITY OF WATERS RESOURCES IN BHUTAN

The snow capped mountains in the north and sub surface water flow collected from seasonal rainfall are two major sources of water for the river systems in Bhutan. There are four major river basins that drain their water into the Indian plains: the Amo Chhu that drains out as the Toorsa river originates in the southern part of the Tibetan Plateau while the Haa Chhu, the Pa Chhu and the Thim Chhu originate in the high glacial mountains of the western region and drains into the Wang Chhu providing water for the Chhukha and Tala Hydropower plants. The Wang Chhu basin lies between Tego La range in the west and Dochu La range in the east. Between Dochu La and Pele La ranges lies the Punatsangchhu Chhu basin. This river has the highest probability of increasing its volume through the outburst of glacial lakes like the Lugi Tsho, Thorthomi Tsho and Rapten Tsho in the higher reaches of Lunana. The Mangde Chhu, Chamkhar Chhu, Kuri and Drangmeri all drain into the Manas and are separated by Yotong La, Thrumshing La and Kori La respectively. Kuri and Drangmeri have their origins in the Tibetan plateau.

1.3.1 Current utilization of water

The volume of water in these rivers fluctuates with the peak flow occurs during the monsoon season from July through September. Most of these rivers flow through deep and narrow valleys making it difficult to tap them for uses other than hydropower. It is only in the Wang Chhu and the Punatsang Chhu basins where a small portion of the water is being tapped for agricultural purposes, before reaching the major knick points. Irrigation for rice is the main need that competes with water requirement of hydropower generation. This is not a big problem in Bhutan since maximum water requirement for paddy coincides with the peak monsoon season. A small fraction of fresh water is bottled by the Bhutan Agro Industries in Thimphu[1]. An initiative has been also taken to bottle the clean spring water at Thinleygang under Thimphu Dzongkhag. Aside from this minor utilization in agriculture and hydropower generation, the value of the fresh water for social recreation, hydrotherapy, and big industrial uses are not tapped as yet for economic gains.

1.3.2 Potential of water

Numerous springs, streams and rivers provide water for irrigation, human consumption, and hydropower generation and in some areas, for industrial use before it drains out into the Indian plains. The country is also known for its hot springs (*tshachhus*), hot stone baths

[1] Production increased from 846,724 in 2004 to 1,466,676 liters in 2006

(*menchhus*) and clean spring water (*drupchhus*) for consumption. The local residents use these hot springs as part of their traditional treatment for diseases and physical ailments. The well known hot springs in high demand are found in Gasa, Punakha, Lunana, Bumthang, Gelephu, Zhemgang and Trongsa (not functional) Dzongkhags. There are also a number of hot stone baths using spring water in various places that are popularly used by the locals for healing purposes including rest and restoration. This brief information suggests that the utilization of these water sites is only known to local residents and no government initiatives have been taken to maximize its use for commercial purposes.

1.4 Glaciers and Glacial Lakes

1.4.1 General

A glacier is huge flowing ice mass. The flow is an essential property in defining glaciers. Usually a glacier develops under conditions of low temperature caused by the cold climate which in itself is now sufficient to create a glacier. There are regions in which the amount of the total depositing mass of snow exceeds the total mass of snow melting during a year in both the polar and high mountain regions. A stretch of such an area is defined as an accumulating area. Thus, snow layers are piled up year after year in the accumulation area because of the fact 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 consequences, the density of the snow layer increased whereby snow finally changes to ice below certain dept at the critical density of approximately 0.83 g 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 0.917 g cm^{-3}. Snow has a density range from 0.01 g $cm-^{3}$ for fresh snow layers just after snowfall to ice at density of 0.83 g 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 attitude, the warmer the Climates. Below a critical altitude, the annual mass of deposited snow melts completely. (*Pradeep K.Mool, Wangda, Samjwal R, Bajracharya,2001*)

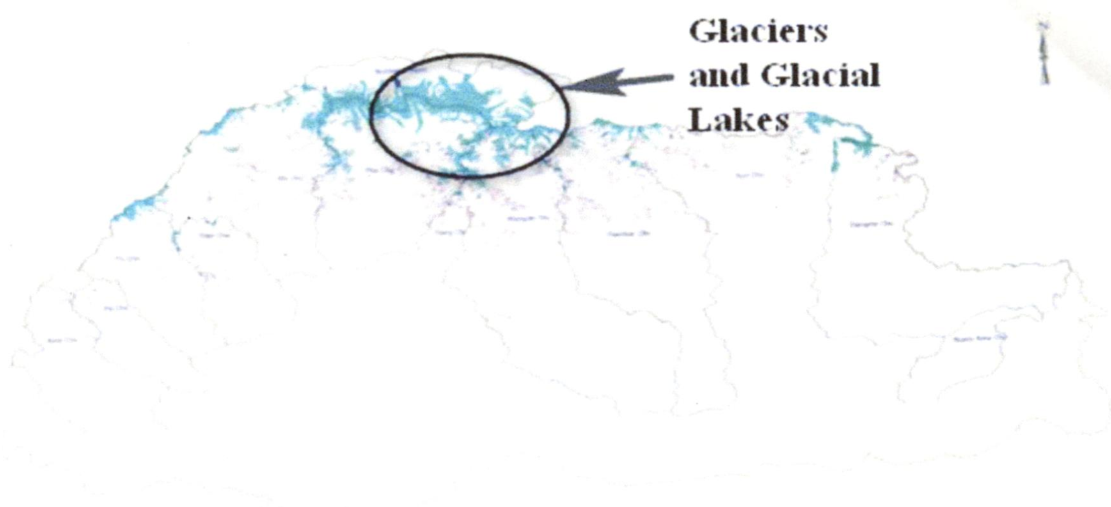


Fig 1.1: Location of Glaciers in Bhutan

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 glaciers 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 are 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 climate changes. A glacier advances when the climate changes to a good summer and a heavy snow fall in winter and the monsoon season. As the glaciers advances it expands and the terminus shifts down to a lower altitude.On the contrary, a glacier retreats when the climates changes to a warm summer and less snowfall. As the glacier retreats, it shrinks and the terminus climbs up to a higher altitude. Thus, climates changes results in a glaciers shifting to another equilibrium size and shape.

Among the basins and sub-basins of the Bhutan Himalayas, Amo chu, and Nyre Ama chu Basin as well as Ha Chu and Dang Chu Sub-Basin have no glaciers. The Pho chu Sub Basin has the highest number of glaciers and the Thim Chu Sub basin the lowest.The northern basin,where the drainage originates in Bhutan and flows towards Tibets (China) have only 59 glaciers but the area occupied by the glaciers in this basin is largest. Altogether there are 677 glaciers with an area of around 1,317sq.km (Fig: 1.1). The estimated ice reserve is 127 km^3.(*Pradeep K.Mool, Wangda, Samjwal R, Bajracharya,2001*)

1.4.2 Important of Glacial Lakes.

Glaciers in Bhutan Himalaya are in general state of degradation and it is necessary to have concern over the glaciers and Glacial Lakes. The glaciers of Bhutan are important storage of freshwater as they accumulate mass in monsoon and winter at higher altitude and provide melt-water at lower elevations. The melt-water contribution of glacier is particularly important during dry seasons to maintain river flow so as to have a continuation of water supply to the population of Bhutan in terms of irrigation, industries, drinking water and livestock etc.

1.4.3 Glacier shrinking

Himalayan glaciers are among the fastest retreating glaciers globally due to the effects of global warming, and this will eventually result in water shortages for hundreds of millions of people who rely on glacier-dependent rivers in China, India and Nepal.Climate change results from a complex process that scientists are only beginning to understand. Glaciers are indicators of long-term temperature changes, with their advances and retreats bearing geological evidence of climatic change. Glaciers in many parts of the world are currently in retreat because of climate change. Ice cores drawn from glaciers can yield further clues to the climates of the past. Vast quantities of fresh water are tied up in the world's many melting glaciers. When Montana's Glacier National Park was created in 1910 it held some 150 glaciers.

Now fewer than 30, greatly shrunken glaciers, remain. Many of the world's freshwater glaciers are shrinking, as warming temperatures melt them away. Some have disappeared all together. The glaciers on both Mount Everest and Mount Kilimanjaro are among those glaciers that are noticeably decreasing as temperatures climb. Some experts are forecasting the melting of half the Arctic's summer sea ice by the end of the 21st century. If Greenland's massive ice sheets were to melt, something that could occur over the very long term, they could raise the sea level by 7 metres (23 feet). Higher temperatures threaten other dangerous consequences: drought, disease, floods, and lost ecosystems. And from sweltering heat to rising seas, global warming's effects have already begun.

1.5 Problem Identification

GLOFs: the most serious natural hazard potentials with 25 lakes potentially dangerous out of about 3000 glacier lakes. Hazards due to GLOF flash floods are likely to increase in intensity with the impacts of climate change. The following phenomena are existing in Bhutan

- Glacial Lakes are forming with increasing number due to the increasing rate of melting/retreating of Glaciers.
- Global warming has accelerated glacial retreat and therefore expansion of Glacial lakes.
- The basins of Mochu, Pochu, Mangde chu, Chamkhar chu and Kuri chu pose threats to the lives, livelihoods of people living in the valleys and low lying river plains.
- At present scenario, the Glacial Lakes located at the source of Pochu give a great treats to the People of Bhutan living at the lower valley (Punkha).

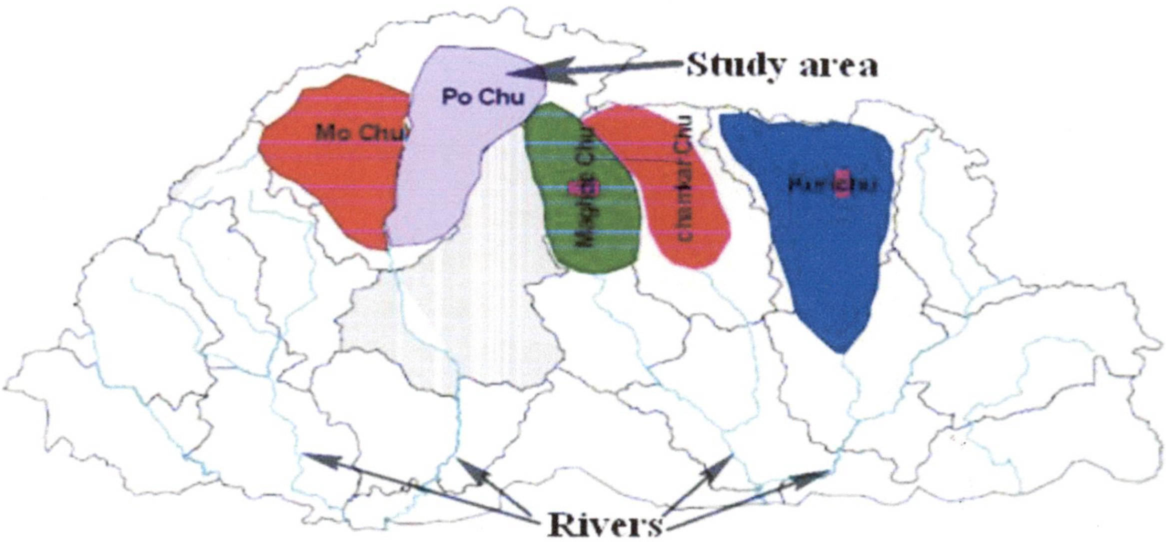


Fig 1.2: River Basin Resources of Glaciers in the study area

The criteria for identifying potentially dangerous glacial lakes are based on field observations, processes and records of past events, geomorphologic and geotechnical characteristics of the lake and surroundings, and other physical conditions. The potentially dangerous lakes were identified based on the conditions of lakes, dams, associated mother glaciers, and topographic features around the lakes and glaciers. From the past study, 24 glacial lakes have been identified as potentially dangerous based on the analysis of data using different criteria and the study of topographic maps and satellite images.

1.6 Objectives

1. Assessment of change in climatic parameters by Trend Analysis by Mann Kendall Statistics Test and Sen's slope estimation of both temperature (^{o}C) and rainfall (mm).

2. To study the Retreating rate of Glaciers/shifting of toes of Glaciers of Potential glacial lakes (Lunana region)
3. To study the variation of glaciers thickness for different years and volume of the glacial lakes for different years.
4. To study the expansion of Glacial Lakes located at the Pochu basins.
5. To study the changes of Land use of whole watershed area of the study area.
6. To model the River (Pochu) with unsteady flow analysis to see the water profile of the river which has originated from the glacial lakes

1.7 Organization of Dissertation

My study mainly stressed upon the following organization chapters and it tells you a very glimpse of my overall view of Dissertation.

Chapter I: Introduction and Objectives of study.

Chapter II: Literature Review on Climate change and causes of it, its impacts on water resources and also climate change and its impact on glaciers.

Chapter III: Brief description of study area and Data availability.

Chapter IV: It contains the Methodology of my main study and introduction of GIS and HEC-GeoRAS for cross-sections extraction and also the HEC-RAS (hydraulic engineering centre's river analysis system) and Simulation of unsteady flow of Pochu (river).

Chapter V: It discusses the Statistical Method with Historical Data which provides the trends analysis.Calibration and validation of the assessment of glaciers and glacial Lakes and also the unsteady modeling of the River (Pochu).

Chapter VI: Conclusion and future scope of study as experienced during my thesis.

CHAPER 2

LITERATURE REVIEW

2.1 CLIMATE SYSTEM

Climate encompasses the statistics of temperature, humidity, atmospheric pressure, wind, rainfall, atmospheric particles count and other meteorological elements in a given area over long periods of time. Climate can be contrasted to weather, which is the present condition of these same elements and their variations over periods up to two weeks.

The climate of a location is affected by its latitude, terrain, and altitude, as well as nearby water bodies and their currents. Climates can be classified according to the average and the typical ranges of different variables, most commonly temperature and precipitation. The most commonly used classification scheme was originally developed by Wladimir Köppen. The Thornthwaite system, in use since 1948, incorporates evapotranspiration in addition to temperature and precipitation information and is used in studying animal species diversity and potential impacts of climate changes. The Bergeron and Spatial Synoptic Classification systems focus on the origin of air masses that define the climate of a region.

Paleoclimatology is the study of ancient climates. Since direct observations of climate are not available before the 19th century, paleoclimates are inferred from *proxy variables* that include non-biotic evidence such as sediments found in lake beds and ice cores, and biotic evidence such as tree rings and coral. Climate models are mathematical models of past, present and future climates.

2.2 DEFINATION OF CLIMATE CHANGE

Climate (from Ancient Greek *klima*, meaning *inclination*) is commonly defined as the weather averaged over a long period of time.The standard averaging period is 30 years, but other periods may be used depending on the purpose. Climate also includes statistics other than the average, such as the magnitudes of day-to-day or year-to-year variations. The Intergovernmental Panel on Climate Change (IPCC) glossary definition is: *Climate in a narrow sense is usually defined as the "average weather," or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are* *most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.*

The difference between climate and weather is usefully summarized by the popular phrase "Climate is what you expect, weather is what you get. Over historical time spans there are a number of nearly constant variables that determine climate, including latitude, altitude, proportion of land to water, and proximity to oceans and mountains. These change only over periods of millions of years due to processes such as plate tectonics. Other climate determinants are more dynamic: for example, the thermohaline circulation of the ocean leads to a 5 °C (9 °F) warming of the northern Atlantic ocean compared to other ocean basins. Other ocean currents redistribute heat between land and water on a more regional scale. The density and type of vegetation coverage affects solar heat absorption, water retention, and rainfall on a regional level. Alterations in the quantity of atmospheric greenhouse determine the amount of solar energy retained by the planet, leading to global warming or global cooling. The variables which determine climates are numerous and the interactions complex, but there is general agreement that the broad outlines are understood, at least insofar as the determinants of historical climate change are concerned.

2.3 CAUSES OF CLIMATE CHANGE

2.3.1 Greenhouse gas emissions

Carbon dioxide is undoubtedly, the most important greenhouse gas in the atmosphere. Changes in land use pattern, deforestation, land clearing, agriculture, and other activities have all led to a rise in the emission of carbon dioxide. Many natural and human-made gases contribute to the greenhouse effect that warms the Earth's surface. Water vapor (H_2O) is the most important, followed by carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and the chlorofluorocarbons (CFCs) used in air conditioners and many industrial processes(Koshland 2009). The increasing atmospheric CO_2 concentration is likely the most significant cause of the current warming.

2.3.2 Human Activity and Greenhouse Gases

The world's economy runs on carbon: the "fuel" in fossil fuels. Coal, oil, and natural gas contribute energy to nearly every human endeavor in industrialized nations, and carbon dioxide (CO_2) is a by-product of burning these fuels. Fossil fuels such as oil, coal and natural gas supply most of the energy needed to run vehicles and also generate electricity for industries, households, etc. The energy sector is responsible for about ¾ of the carbon dioxide emissions, 1/5 of the methane emissions and a large quantity of nitrous oxide. It also produces nitrogen oxides (NOx) and carbon monoxide (CO) which are not greenhouse gases but do have an influence on the chemical cycles in the atmosphere that produce or destroy greenhouse gases. Moreover, the changing pattern of land use such as deforestation, for some development oriented projects can significantly increase the amount of atmospheric CO_2 which warms the planet.

2.3.3 Human causes

The Industrial Revolution in the 19th century saw the large-scale use of fossil fuels for industrial activities. These industries created jobs and over the years, people moved from rural areas to the cities. This trend is continuing even today. More and more land that was covered with vegetation has been cleared to make way for houses.Natural resources are being used extensively for construction, industries, transport, and consumption. Consumerism (our increasing want for material things) has increased enormously, creating huge amount of waste. Also, our population has increased to an incredible extent. All this has contributed to a rise in greenhouse gases in the atmosphere.

2.3.4 Carbon dioxide (CO_2)

Carbon dioxide (CO_2) is a colourless, odourless gas that has been present in earth's atmosphere through time in trace amounts ranging from a few hundred to a few thousand parts per million (ppm). Average atmospheric values over the last few hundred thousand years are inferred from ice cores which has was nearly 180 ppm during glacial and 280 ppm during interglacial's (e:g Petit *et al*, 1999). Hurd (2006), Jaworowski (2007) and others have argued that these values are about 30 - 50 per cent lower than the original atmospheric values that they purport to represent, because of the post-depositional diffusion and mixing that occurs within the compacting ice mass. Independent evidence from fossil plant stomata indicates that carbon dioxide levels during the Holocene were variable on a decadal-centennial scale compared with the monotonic curve delineated by the ice cores (Figure 2.1,), and reached at least the present day (post-industrial) value of 380 ppm (Kurschner *et al*, 1996; Wagner, Aaby and Visscher, 2002; Kouwenberg *et al*, 2005) (Figure 2.2). More support for decadal fluctuations of carbon dioxide comes from the compilation and summary of 90 000 historical atmospheric analyses back to the mid-19th century by Beck (2007).

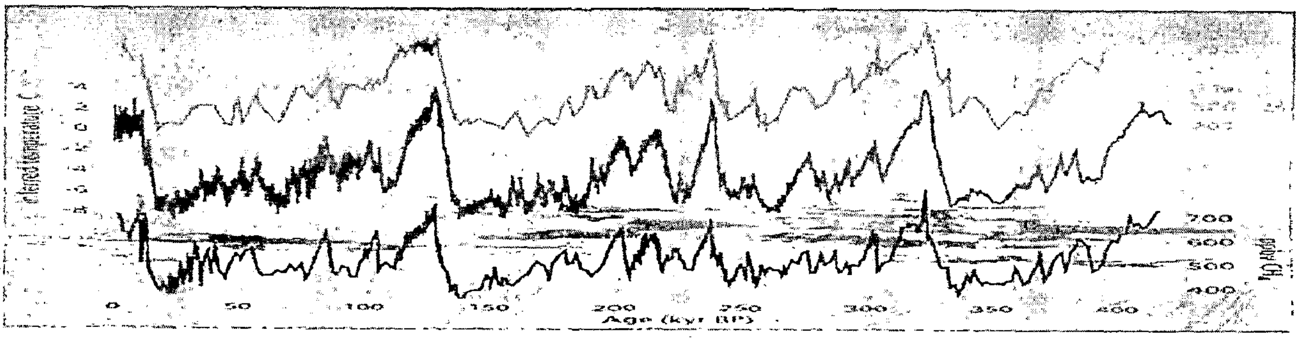


Fig 2.1 - Atmospheric carbon dioxide, temperature and methane levels for the last 420 000 years

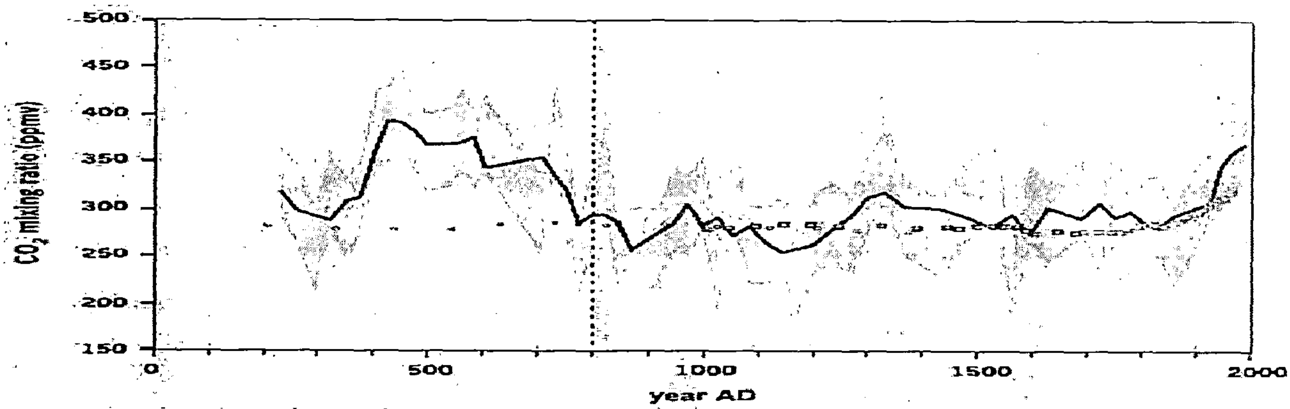


Fig 2.2- Reconstruction of paleo-atmospheric carbon dioxide levels for the last 1800 years

2.4 IMPACTS OF CLIMATE CHANGE ON CRITICAL AREAS

2.4.1 Live stocks

In pastoral and agro-pastoral systems, livestock are key assets for poor people, providing multiple economic, social, and risk management functions. The impacts that climate change will bring about are expected to exacerbate the vulnerability of livestock systems and to reinforce existing factors that are simultaneously affecting livestock production systems such as rapid population and economic growth, increased demand for food (including livestock) and products(Gill and Smith, 2008), increased conflict over scarce resources (i.e. land tenure, water, biofuels, etc). For rural communities losing livestock assets might lead to the collapse into chronic poverty with long-term effects on their livelihoods.

Table 2.1: Impacts of climate change on livestock and livestock system (Thornton et al, 2008)

FACTOR	IMPACTS
Biodiversity: (genetics and breeding)	In places, will accelerate the loss of genetic and cultural diversity in agriculture already occurring as a result of globalization, (Ehrenfeld, 2005), in crops as well as domestic animals. A 2.5 °C increase in global temperature wi ll see major losses: 20-30% of all plant and animal species assessed could be at high risk of extinction (IPCC, 2007). Ecosystems and species show a wide range of vulnerabilities to climate change, depending on the imminence of exposure to ecosystem-specific, critical thresholds, but assessments are fraught with uncertainty related to CO_2 fertilization effects etc. Local and rare breeds are at risk of being lost through the impact of climate change and disease epidemics. There are global health implications related to biodiversity loss and many of the anticipated health risks brought about by climate change will be caused by loss of genetic diversity.
Livestock (and human) health:	Major impacts on vector-borne diseases: Expansion of vector populations into cooler areas (in higher altitude areas: malaria and livestock tick-borne diseases) or into more temperate zones (such as bluetongue disease in northern Europe). Changes in rainfall pattern may also influence expansion of vectors during wetter years, leading to large outbreaks of disease (Rift Valley Fever virus in East Africa). It is also leading to climate change. Helminth infections are greatly influenced by changes in temperature and humidity. Climate change may affect trypano tolerance in sub-humid zones of West Africa: could lead to loss of this adaptive trait that has developed over millennia and greater disease risk in the future. There are effects (via changes in crop, livestock practices) on distribution and impact of malaria in many systems and schistosomiasis and lymphatic filariasis in irrigated systems. Increases in heat-related mortality and morbidity (Patz *et al.*, 2005)

Among the direct effects of climate change for example, there will be higher temperatures and changes in rainfall patterns, translating in an increased spread of existing vector-borne diseases and macro parasites of animals as well as the emergence and spread of new diseases. In some areas, climate change may also cause new transmission models; these effects will be felt by both developed and developing countries, but developing countries will be effected mostly because of their lack of resources, knowledge, veterinarian and extension services and research technology development (FAO, 2008).

Some of the indirect effects for example will be brought about by changes in feed resources linked to the carrying capacity of rangelands, the buffering abilities of ecosystems, increased desertification processes, increased scarcity of water resources, lower production of grain, etc. Other indirect effects will be linked to the expected potential shortage of feed due to a rapid increase in production competition between food, feed, fuel and land use systems.

In a recent paper, Thornton *et al.* 2008 have provided an overview of some direct and indirect impacts of climate change on livestock and livestock systems. This is exemplified in Table 2.1.

2.4.2 Aquatic life

The impacts on aquatic systems especially marine systems, that have been comprehensively analysed (to the extent permitted by available data) in two recent reviews commissioned by the Australian Greenhouse Office (Hobday and Matear (eds), 2005 and Hobday *et al.*, 2006). These and other data from the Bureau of Meteorology (2007), Fisheries Research and Development Corporation (2007), Hennessy *et al.*, (2007), warmer temperatures will change species distributions (food web dynamics) as poikilothermic fish and invertebrates attempt to thermo-regulate behaviourally by migrating to cooler water in geographically constrained rivers and lakes. Metabolic rates increase with the consequent need for more food to support this higher metabolism

2.4.3 Aquatic Ecosystems

The changing freshwater flow to estuaries and the predicted upstream migration of salt water will alter aquatic habitats and change the distribution of plants (wetlands) and aquatic animals (Bunn and Arthington, 2002, Hall and Burnes, 2002 and Schallenberg *et al.*, 2003). Tidal wetlands (particularly saltmarsh Adam, 2002), which are also important nursery habitat, will be reduced in extent because there is rarely the capacity for them to expand landward as sea level rises. In Estuaries Sea grasses growth rates are temperature and light dependant and redistribution of sea grass habitats will occur as a consequence of the increased temperature and changing light regime (Short and Neckles, 1999).

2.4.4 Wild Harvest Fisheries

The aquatic ecosystem changes discussed above will have a direct effect on wild harvest fisheries as the distribution and abundance of aquatic plant and animal species vary in parallel with the habitat changes. In addition recruitment and catch rates in several fish species are associated with seasonal to inter annual variability of westerly winds and strong wind events (Thresher *et al.*, 1989, 1992 and Thresher, 1994). A decline in wind due to a pole ward shift in climate systems underlies recent stock declines off southeastern Australia and western Tasmania, and these are linked to changes in larval growth rates and recruitment of juveniles in two fish species around Tasmania (Koslow and Thresher, 1999 and Thresher, 2002). Reductions in upwelling of nutrients and extension of warm water along the east Australian coast are likely to reduce prey species abundance, upon which many other species are reliant, including carnivorous fishes, seals and seabirds (CSIRO, 2002).

2.4.5 Sustainable food

Research shows that the global population is growing with the result demands are increasing for food production. In terms of global emissions, agriculture and changes in current land use such as deforestation are believed to be responsible for 25% of CO_2, 65% of methane and 90% of nitrous oxide emitted (NIEL 2009). In Ireland, North and South, agriculture is an important part of the economy and way of life, but it also represents a large contribution to total GHG emissions. To meet UN targets by 2020 there will need to be significant improvements in reducing emissions from agricultural activities (EEA 2010).

The reduction of greenhouse gas emissions in the food and agriculture sector could also help to prevent the burden of chronic disease. The 20th century change from largely plant-based diets to energy-dense diets high in fat and animal foods has played a key role in the upsurge of diet-related, preventable health problems such as heart disease, diabetes, some cancers and obesity (Lancet 2009).

2.5 HUMAN HEALTH AND WELFARE EFFECT FROM CLIMATE CHANGE.

2.5.1 Human Health

Warm temperatures and extreme weather already cause and contribute to adverse human health outcomes through heat-related mortality and morbidity, storm-related fatalities and injuries, and disease. In the absence of effective adaptation, these effects are likely to increase with climate change.

Depending on progress in health care and access, infrastructure, and technology, climate change could increase the risk of heat wave deaths, respiratory illness through exposure to aeroallergens and ozone, and certain diseases (CCSP, 2008b; Confalonieri et al, 2007). Studies in temperate areas (which would include large portions of the United States) have shown that climate change is projected to bring some benefits, such as fewer deaths from cold exposure. The balance of positive and negative health impacts as a result of climate change will vary from one location to another and will alter over time as climate change continues (CCSP, 2008b).

2.5.2 Air Quality

Surface air concentrations of air pollutants are highly sensitive to winds, temperature, humidity, and precipitation (Denman et al., 2007). Climate change can be expected to influence the concentration and distribution of air pollutants through a variety of direct and indirect processes, including the modification of biogenic emissions, the change of chemical reaction rates, wash-out of pollutants by precipitation, and modification of weather patterns that influence pollutant buildup.

In summarizing the impact of climate change on ozone and particulate matter (PM), the IPCC (Denman et al., 2007) states that "future climate change may cause significant air quality degradation by changing the dispersion rate of pollutants, the chemical environment for ozone and PM generation and the strength of emissions from the biosphere, fires and dust."

2.5.3 Food production and agriculture

The CCSP report on U.S. agriculture (Backlund et al., 2008a) made the following general conclusions for the United States:

- With increased CO_2 and temperature, the life cycle of grain and oilseed crops will likely progress more rapidly. But, as temperature rises, these crops will increasingly begin to experience failure, especially if climate variability increases and precipitation lessens or becomes more variable.
- The marketable yield of many horticultural crops (e.g., tomatoes, onions, fruits) is very likely to be more sensitive to climate change than grain and oilseed crops.
- Climate change is likely to lead to a northern migration of weeds. Many weeds respond more positively to increasing CO_2 than most cash crops, particularly C_3 "invasive" weeds. Recent research also suggests that glyphosate, the most widely

used herbicide in the United States, loses its efficacy on weeds grown at the increased CO_2 levels likely in the coming decades.

- Disease pressure on crops and domestic animals will likely increase with earlier springs and warmer winters, which will allow proliferation and higher survival rates of pathogens and parasites. Regional variation in warming and changes in rainfall will also affect spatial and temporal distribution of disease.
- Projected increases in temperature and a lengthening of the growing season will likely extend forage production into late fall and early spring, thereby decreasing need for winter season forage reserves. However, these benefits will very likely be affected by regional variations in water availability.

2.5.4 Forestry

The CCSP report addressing forestry and land resources (Ryan et al., 2008) notes climate strongly influences forest productivity, species composition, and the frequency and magnitude of disturbances that impact forests and made the following general conclusions for the United States:

- Climate change has very likely increased the size and number of forest fires, insect outbreaks, and tree mortality in the interior West, the Southwest, and Alaska, and will continue to do so. An increased frequency of disturbance (such as drought, storms, insect outbreaks, and wildfire) is at least as important to ecosystem function as incremental changes in temperature, precipitation, atmospheric CO_2, nitrogen deposition, and ozone pollution. Disturbances partially or completely change forest ecosystem structure and species composition, cause short-term productivity and carbon storage loss, allow better opportunities for invasive alien species to become established, and command more public and management attention and resources.
- Rising CO_2 will very likely increase photosynthesis for forests, but the increased photosynthesis will likely only increase wood production in young forests on fertile soils. Nitrogen deposition and warmer temperatures have very likely increased forest growth where water is not limiting and will continue to do so in the near future.
- The combined effects of expected increased temperature, CO_2, nitrogen deposition, ozone, and forest disturbance on soil processes and soil carbon storage remain unclear.

2.5.5 Sea Level Rise and Coastal Areas

The IPCC (Field et al., 2007) concluded the following when considering how climate change effects, including sea level rise, may result in impacts to North American coasts: Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution (very high confidence). A sea level is rising along much of the coast, and the rate of change will increase in the future, exacerbating the impacts of progressive inundation, storm-surge flooding, and shoreline erosion.

Storm impacts are likely to be more severe, especially along the Gulf and Atlantic coasts. Salt Marshes, other coastal habitats, and dependent species are threatened by sea level rise, fixed structures blocking landward migration, and changes in vegetation. Population growth and rising value of infrastructure in coastal areas increases vulnerability to climate variability and future climate change.

2.5.6 Energy, Infrastructure, and Settlements

According to the IPCC (Wilbanks et al., 2007), "industries, settlements and human society are accustomed to variability in environmental conditions, and in many ways they have become resilient to it when it is a part of their normal experience. Environmental changes that are more extreme or persistent than that experience, however, can lead to vulnerabilities, especially if the changes are not foreseen and/or if capacities for adaptation are limited.

Climate change is likely to affect U.S. energy use and energy production, physical infrastructures, and institutional infrastructures and will likely interact with and possibly exacerbate ongoing environmental change and environmental pressures in settlements (Wilbanks et al., 2007), particularly in Alaska where indigenous communities are facing major environmental and cultural impacts on their historic lifestyles (ACIA, 2004). Climate warming will be accompanied by decreases in demand for heating energy and increases in demand for cooling energy (Karl et al., 2009). These changes will vary by region and by season, but they will affect household and business energy costs and their demands on energy supply institutions. The latter will result in significant increases in electricity use and higher peak demand in most regions (Karl et al., 2009). Other effects on energy consumption are less clear (CCSP, 2007a).

2.6 CLIMATE CHANGE AND WATER RESOURCES

Water is involved in all components of the climate system (atmosphere, hydrosphere, cryosphere, land surface and biosphere). Hence climate change affects water through a number of mechanisms. This section discusses observations of recent changes in water-related variables, and projections of future changes.

The particular interest for projections of water resources, with or without climate change, are possible changes in dam construction and decommissioning, water supply infrastructure, wastewater treatment and reuse, desalination, pollutant emissions and land use, particularly with regard to irrigation. Irrespective of climate change, new dams are expected to be built in developing countries for hydropower generation as well as water supply, even though their number is likely to be small compared to the existing 45,000 large dams. In saying this, however, the impacts of a possible future increase in hydropower demand have not been taken into account (World Commission on Dams, 2000; Scudder, 2005).

2.6.1 Precipitation (including extremes) and water vapour

Trends in land precipitation have been analysed using a number of data sets, notably the Global Historical Climatology Network (GHCN: Peterson and Vose, 1997), but also the

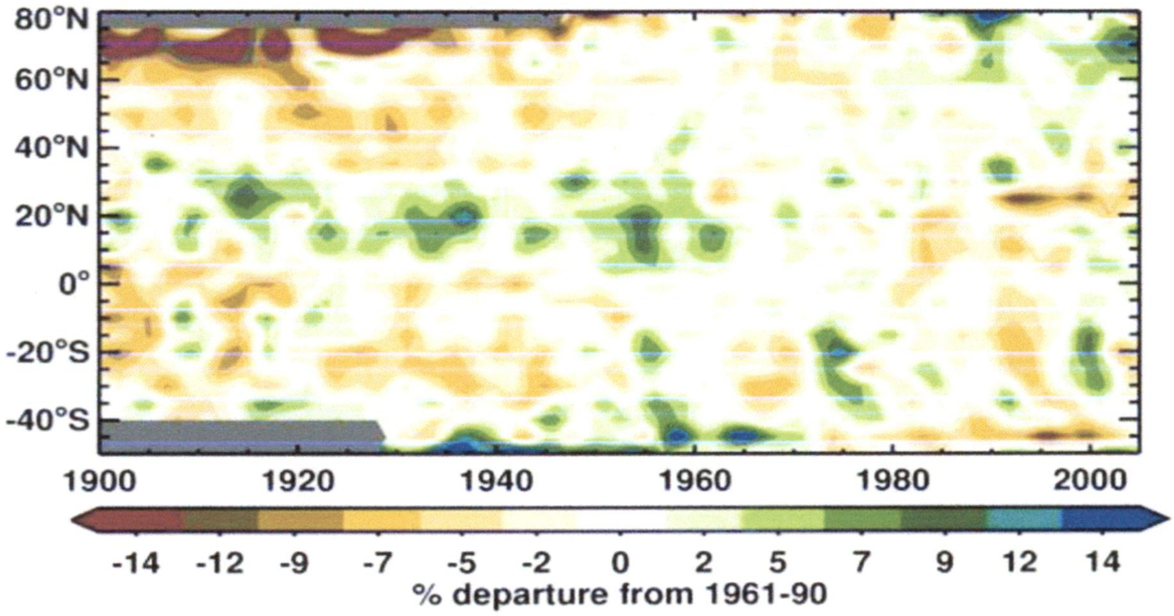


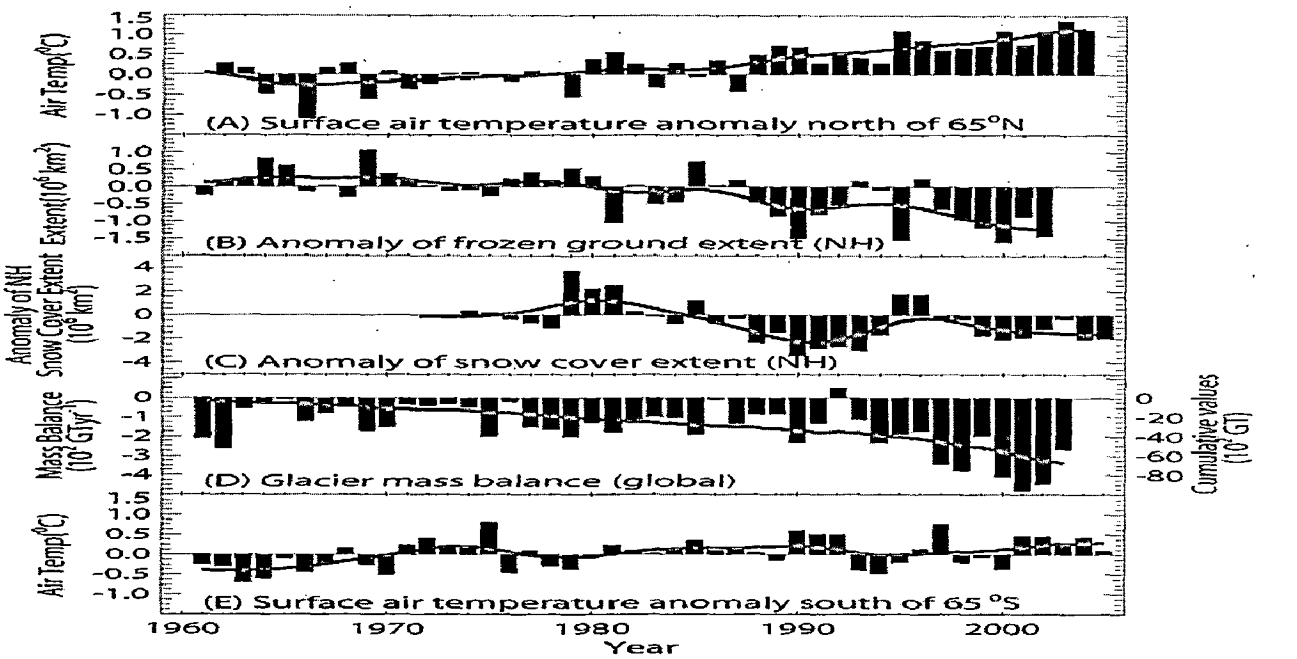
Figure 2.3: *Latitude-time section of average annual anomalies for precipitation (%) over land from 1900 to 2005, relative to their 1961 to 1990 means. Values are averaged across all longitudes and are smoothed with a filter to remove fluctuations less than about 6 years. The colour scale is non-linear and grey areas indicate missing data.*

Precipitation Reconstruction over Land (PREC/L: Chen et al., 2002), the Global Precipitation Climatology Project (GPCP: Adler et al., 2003), the Global Precipitation Climatology Centre (GPCC: Beck et al., 2005) and the Climatic Research Unit (CRU: Mitchell and Jones, 2005). Precipitation over land generally increased over the 20th century between 30°N and 85°N, but notable decreases have occurred in the past 30 to 40 years from 10°S to 30°N. Salinity decreases in the North Atlantic and south of 25°S suggest similar precipitation changes over the ocean.

From 10°N to 30°N, precipitation increased markedly from 1900 to the 1950s, but declined after about 1970. There are no strong hemispheric-scale trends over Southern Hemisphere extratropical land masses. At the time of writing, the attribution of changes in global precipitation is uncertain, since precipitation is strongly influenced by large-scale patterns of natural variability. [WGI 3.3.2.1]

2.6.2 Snow and land ice

The cryosphere (consisting of snow, ice and frozen ground) on land stores about 75% of the world's freshwater.



Figur2.4: *Anomaly time series (departure from the long-term mean) of polar surface air temperature (A and E), Northern Hemisphere (NH) seasonally frozen ground extent (B), NH snow cover extent for March-April (C), global glacier mass balance (D). The solid red line in D denotes the cumulative global glacier mass balance; otherwise it represents the smoothed time series. [Adapted from WGI FAQ 4.1]*

In the climate system, the cryosphere and its changes are intricately linked to the surface energy budget, the water cycle and sea-level change. More than one sixth of the world's population lives in glacier or snowmelt fed river basins (Stern, 2007) [WGII 3.4.1]. Figure 2.4 shows cryosphere trends, indicating significant decreases in ice storage in many components.

2.6.3 Snow cover, frozen ground, lake and river ice

Snow cover has decreased in most regions, especially in spring and summer. Northern Hemisphere snow cover observed by satellites over the 1966 to 2005 period decreased in every month except November and December, with a stepwise drop of 5% in the annual mean in the late 1980s. Declines in the mountains of western North America and in the Swiss Alps have been largest at lower elevations. In the Southern Hemisphere, the few long records or proxies available mostly show either decreases or no changes in the past 40 years or more. [WGI 4.2.2]

2.6.4 Glaciers and Ice caps

On average, glaciers and ice caps in the Northern Hemisphere and Patagonia show a moderate but rather consistent increase in mass turnover over the last half century and substantially increased melting [WGI]. As a result, considerable mass loss occurred on the majority of glaciers and ice caps worldwide (Figure 2.5) with increasing rates: from 1960/1961 to 1989/1990 the loss was 136 ± 57 Gt/yr (0.37 ± 0.16 mm/yr sea level equivalent, SLE), between 1990/1991 and 2003/2004 280 ± 79 Gt/yr (0.77 ± 0.22 mm/yr SLE). The widespread 20th century shrinkage appears to imply widespread warming as the primary cause although in the tropics changes in atmospheric moisture might be contributing. There is evidence that this melting has *very likely* contributed to observed sea-level rise. [WGI]
Formation of lakes is occurring as glacier tongues retreat from prominent Little Ice Age (LIA) moraines in several steep mountain ranges, including the Himalayas, the Andes, and the Alps. These lakes have a high potential for glacial lake outburst floods. [WGII]

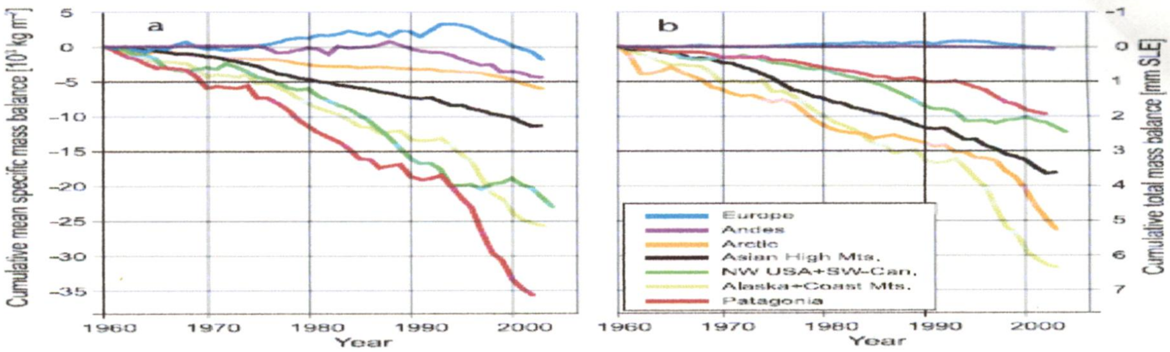


Figure2.5: *Cumulative mean specific mass balances (a) and cumulative total mass balances (b) of glaciers and ice caps, calculated for large regions (Dyurgerov and Meier, 2005). The mass balance of a glacier is the sum of all mass gains and losses during a hydrological year. Mean specific mass balance is the total mass balance divided by the total surface area of all glaciers and ice caps of a region, and it shows the strength of change in the respective region. Total mass balance is presented as the contribution from each region to sea-level rise. [WGI 4.5.2,]*

2.6.5 Sea level

Global mean sea level has been rising and there is *high confidence* that the rate of rise has increased between the mid-19th and the mid-20th centuries. The average rate was 1.7 ± 0.5 mm/yr for the 20th century, 1.8 ± 0.5 mm/yr for 1961 to 2003, and 3.1 ± 0.7 mm/yr for 1993 to 2003. It is not known whether the higher rate in 1993 to 2003 is due to decadal variability or to an increase in the longer-term trend. Spatially, the change is highly non-uniform; e.g. for 1993-2003 rates in some regions were up to several times the global mean rise, while in other regions sea levels fell. [WGI 5.ES]

Rising sea level potentially affects coastal regions but attribution is not always clear. Global increases in extreme high water levels since 1975 are related to both mean sea-level rise and large-scale inter decadal climate variability (Woodworth and Blackman, 2004) [WGII 1.3.3].

2.6.6 Evapotranspiration

There are very limited direct measurements of actual evapotranspiration over global land areas, while global analysis products are sensitive to the type of analysis and can contain large errors, and thus are not suitable for trend analysis. Therefore, there is little literature on observed trends in evapotranspiration, whether actual or potential. [WGI 3.3.3]

2.6.7 Pan evaporation

Decreasing trends during recent decades are found in sparse records of pan evaporation (measured evaporation from an open water surface in a pan, a proxy for potential evapotranspiration) over the USA (Peterson et al., 1995; Golubev et al., 2001; Hobbins et al.,2004), India (Chattopadhyay and Hulme, 1997), Australia (Roderick and Farquhar, 2004), New Zealand (Roderick and Farquhar, 2005), China (Liu et al., 2004a; Qian et al., 2006b) and Thailand (Tebakari et al., 2005). Pan measurements do not represent actual evaporation (Brutsaert and Parlange, 1998), and any trend is more likely caused by decreasing surface solar radiation (over the USA and parts of Europe and Russia) and decreased sunshine duration over China that may be related to increases in air pollution and atmospheric aerosols and increases in cloud cover. [WGI 3.3.3, Box 3.2]

2.6.8 Actual evapotranspiration

The TAR reported that actual evapotranspiration increased during the second half of the 20th century over most of the dry regions of the USA and Russia (Golubev et al., 2001), resulting from greater availability of surface moisture due to increased precipitation and larger atmospheric moisture demand due to higher temperature. Using observations of precipitation, temperature, Cloudiness-based surface solar radiation and a comprehensive land surface model, (Qian et al. 2006a) it has found that global land evapotranspiration closely follows variations in land precipitation. Global precipitation values peaked in the early 1970s and then decreased somewhat, but reflect mainly tropical values, and precipitation has increased more generally over land at higher latitudes. Changes in evapotranspiration depend not only on moisture supply but also on energy availability and surface wind. [WGI 3.3.3]

2.6.9 Soil moisture

Historical records of *in situ* measured soil moisture content are available for only a few regions and are often very short [WGI 3.3.4]. Among more than 600 stations from a large variety of climates, Robock et al. (2000) identified an increasing long-term trend in surface (top 1 m) soil moisture content during summer for the stations with the longest records, mostly located in the former Soviet Union, China, and the central USA. The longest records available, from the Ukraine, show overall increases in surface soil moisture but increases are less marked in recent decades (Robock et al., 2005). The initial approach in estimating soil moisture has been to calculate Palmer Drought Severity Index (PDSI) values from observed precipitation and temperature. PDSI changes are discussed in Section 3.1.2.4.. [WGI Box 3.1, 3.3.4]

2.6.10 Runoff and river discharge

A large number of studies have examined potential trends in measures of river discharge during the 20th century, at scales ranging from catchment to global. Some have detected significant trends in some indicators of flow, and some have demonstrated statistically significant links with trends in temperature or precipitation. Many studies, however, have found no trends or have been unable to separate out the effects of variations in temperature and precipitation from the effects of human interventions in the catchment.

The methodology used to search for trends can also influence results. For example, different statistical tests can give different indications of significance, different periods of record (particularly start and end dates) can suggest different rates of change, and failing to allow for cross-correlation between catchments can lead to an overestimation of the numbers of catchments showing significant change. Another limitation of trend analysis is the availability of consistent, quality-controlled data. Available stream flow gauge records cover only about two-thirds of the global actively drained land area and often contain gaps and vary in record length (Dai and Trenberth, 2002).

2.7 CLIMATE CHANGE AND GLACIERS

2.7.1 General

The Earth is affected by rapid climate changes in response to anthropogenic greenhouse gas emissions, with observed global warming and an enhanced hydrological cycle. The cryosphere is undergoing rapid melt as a result of this warming. A meeting for discussing the effects of climate change on glaciers and glacial environments, and their associated impacts was held in Rome, Italy, in July 6-7 of 2007, under the auspices of the Chilean Embassy, the collaboration of ENEA, Ente per le Nuove tecnologie, l'Energia e l'Ambiente, Comitato Glaciologico Italiano (CGI), Centro de Estudios Científicos (CECS) and Instituto Antártico Chileno (INACH). Expected outcomes of the meeting are an evaluation of the present situation of mountain glaciers in the Andes, the Alps and Scandinavia, and of the Antarctic ice sheet, and recommendations for future work for studying and monitoring these ice masses.

Holocene climate change is one of the focus themes both in paleoclimate modeling and proxy data reconstruction communities. By examining 50 globally distributed paleoclimate records, Mayewski et al. (2004) revealed as many as six periods of significant rapid climate change during the Holocene which were synchronous of the whole Earth. It is suggested that changes in insolation related both to Earth's orbital variations and to solar variability played a central role in the global scale changes in climate of the last 11.5 cal kyr (Mayewski et al., 2004). This insolation driving mechanism in the Holocene climate change is supported by climate modeling experiments of African-Asian monsoon climate (e.g. Kutzbach and Otto-Bliesner, 1982; Kutzbach and Guetter, 1986; COHMAP Members, 1988; Joussaume et al., 1999; Otto-Bliesner, 1999; Weber et al., 2004). However, external forcing, e.g. the Earth's orbital variations and the solar variability, can be amplified and modified through a number of feedbacks within the climate system leading to marked climate variations in the Holocene (Foley et al., 1994; TEMPO Members, 1996; Claussen and Gayler, 1997; Ganopolski et al., 1998b; Wang, 1999). The atmosphere vegetation feedback is an important amplifying factor of the North Africa's abrupt climate transition from a wet phase to a dry phase starting at around 6 kyr BP (Texier et al., 1997; Claussen et al., 1999). The positive oceanic feedback is another factor for enhanced African summer monsoon in early Holocene (Kutzbach and Liu, 1997; Liu et al., 2003). Studies from lake sediment pollen and carbonate records showed the arid phase in South Asia probably started around 5 kyr BP (Maxwell, 2001; Singh, 2002), coinciding with a stepwise weakening of the southwest monsoon (Gupta and Anderson, 2005), which was closely linked to North Atlantic cold spells, e.g. the millennial-scale cold events.

2.7.2 Mountain Glaciers as an indicator of climate change

Mountain glaciers are key indicators and unique demonstration objects of global climate change (Houghton and others, 2001). As a consequence, they are an 'essential climate variable' in the terrestrial part of the Global Climate Observing System (GCOS/GTOS). The corresponding monitoring network, the Global Terrestrial Network for Glaciers (GTN-G), is run by the World Glacier Monitoring Service (WGMS) in close cooperation with the Global Land Ice Measurements from Space (GLIMS) initiative (Bishop and others, 2004; Bamber, 2006; Ka¨a¨b, 2006; cf. GCOS, 2003, 2004; Haeberli, 2004).

The monitoring network uses an integrated, multi-level strategy, which helps to bridge the gap between detailed local process-oriented studies and global coverage by combining in situ measurements (mass balance, length change) with remote-sensing data and digital terrain information (areas, elevations, topographic parameters, inventories) and numerical modelling (thickness estimates, energy balance, flow modelling). The primary aim of this paper is to illustrate this concept by integrating a rich basis of existing data for the case of the European Alps, where especially dense information has been available through historical times.

2.7.3 Modeled Climate-Induced Glacier Change in Glacier

Since its establishment in 1910, Glacier Park has lost most of its glaciers. Over two-thirds of the estimated 150 glaciers existing in 1850 had disappeared by 1980 (Carrara and McGimsey 1981). Furthermore, over that same time period, the surviving glaciers were greatly reduced in area (figure 3). The local summer mean temperature increased 1.66°C between 1910 and 1980. These events reflect a worldwide pattern of glacial retreat and regional climatic change that, in aggregate, has been viewed as evidence of global warming. The global retreat of mountain glaciers could have direct consequences for humanity. Fifty percent of the freshwater that humans consume yearly comes from mountains (Liniger et al. 1998). Disappearing glaciers have a significant impact on mountain hydrology (Fagre et al. 1997) and leave new terrain for plant colonization. In many parts of the world, distant mountain glaciers provide lowland rivers with the hydrological base flow (i.e., the minimum flow when snowmelt's contribution to flow is at its lowest) upon which agriculture depends in late summer. The reduction in the Zongo Glacier in the Bolivian Andes has created water-supply problems for downstream communities (Liniger et al. 1998). Globally, a 10- to 25-centimeter (cm) rise in sea level has been recorded during this century; Meier (1984) and others attribute part of this rise to the worldwide retreat of alpine glaciers. Thus, even those who live far from mountains have experienced the consequences of melting glaciers.

2.7.4 Glaciers, Ice Sheets, and Climate Change

Glaciers and **ice sheets** both affect and are affected by changes in Earth's climate. They are frozen fresh-water reservoirs that change volume in response to changes in temperature and snowfall. Were the ice sheets in Greenland and Antarctica to melt entirely, global sea level would rise about 75 meters (250 feet). Those great polar ice sheets also contribute to the formation of cold, salty sea water that sinks to fill the deep ocean. When the ice forms, it uses only water; the dissolved salts are left behind, increasing the water's salinity. And ice and snow play a role in the global energy balance by reflecting from 60 to 90 percent of the solar radiation they receive. On a scale more relevant to peoples' daily lives, the seasonal melting of mountain glaciers contributes to summertime river flow and to the ongoing sea-level rise.

Today, permanent ice covers a little less than 10 percent of Earth's land surface, yet contains almost 87 percent of its fresh water. The majority of the ice, 29×10^{6} cubic kilometers (approximately 7 million cubic miles), is in Antarctica. The Greenland Ice Sheet holds 2.95×10^{6} cubic kilometers (706,000 cubic miles) of ice, whereas glaciers and **ice caps** amount to about 0.18×10^{6} cubic kilometers (43,000 cubic miles). Although glaciers and ice caps make up less than 1 percent of Earth's terrestrial ice volume, their small size allows them to respond rapidly to climate change Glaciers normally experience seasonal melting, which produces melt water important to the hydrologic cycle. The Columbia Glacier, a tidewater glacier (i.e., a glacier that ends in the sea) near Valdez, Alaska, has shown more extensive changes, losing ice and retreating nearly 12 kilometers (7.5 miles) from 1982 to 2000).

2.7.5 Modern Glacier Retreat

Mountain glaciers are always changing because they tend towards balance with ever-changing snowfall and melting rates. Some special glaciers change volume for other reasons. "Surge-type glaciers" experience rapid speed-ups that move ice downstream quickly, thinning the glacier, followed by quiescent periods in which the ice thickens once again. "Tidewater glaciers" end as a floating ice tongue in a lake or bay, where interaction with the Lake Bottom or seafloor, and iceberg calving events may complicate their flow.

Yet despite all the possible complications, glaciologists conclude that worldwide, glaciers are retreating rapidly as climate warms. For example, the glaciers of Mount Kilimanjaro, about which Hemingway wrote in 1938, are predicted to be gone by 2020. Ice first started to accumulate on that mountain nearly 12,000 years ago. Alaskan glaciers, measured with laser from a low-flying airplane, are thinning rapidly and contributing as much as 0.14 millimeters (0.005 inches) per year to sea level. The thinning rate has increased within the last decade. In Antarctica, ice-shelf collapse along its northward-reaching peninsula has also been linked to ongoing warming. Glacier retreat also is being monitored in the Himalayas, where increased melting can lead to flood risks for people living downstream. Around the world, glaciers are retreating in response to warming weather, and water resources and sea level will continue to be affected as they do.

2.7.6 Ice Thicknesses and Volumes

Once the distribution of glaciers as a function of their individual areas has been defined, using glacier inventories and a scaling analysis, the distribution of glacier thicknesses and volumes can be calculated. These are important for projecting the glacier contribution to sea level rise in future years; the areas of thin glaciers will decrease rapidly with wastage, but thick glaciers will continue to produce melt water long in the future. We use a volume/area scaling algorithm (Bahr et al., 1997; Macheret et al., 1999) with bins 2n in area to estimate glacier volume and thickness distributions and thus their likely area changes with further melting. This value for total glacier volume is considerably higher than the values reported by some other authors.

Traditionally, attention has been paid to variations in the length of glaciers — their advance and retreat (e.g., Forell, 1895; Oerlemans, 1994, 2005; Haeberli, 1995). Although useful for demonstrating changes, these data give only crude measures of the glacier's overall changes unless detailed knowledge is available for modeling their dynamic response to mass balance change. This knowledge is available for only a few glaciers, and therefore these advance/retreat histories are of limited use for large-scale syntheses of year-to-year climate change or sea-level rise. Here we direct our attention to the annual (or net) balance of glaciers; this is a direct measure of the exchange of ice mass between the atmosphere and the land/ocean.

2.7.7 Extracting a Climate Signal from 169 Glacier

The number of records reveals a strong increase at the end of the 19th century, both for the Alps and for all other glaciers (Fig. 2.6a). Stacking all records yields a curve for the change in mean glacier length (Fig.2.6b).

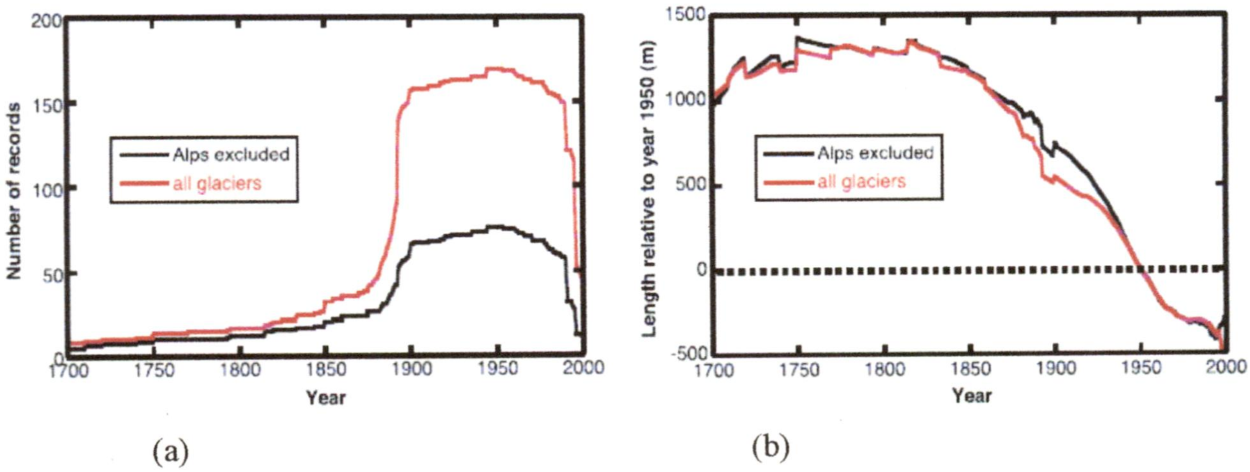


Fig2.6 :(a) Number of records for the last 300 years.The decline after 1990 is due to a large delay in the reporting and publishing of data in a suitable form. (b) Stacked records of glacier length.

The curve was not smoothed, implying that some irregularities occur when a glacier with a large change in length is added to the sample (or disappears from the sample at the very end). The curve for all glaciers outside the Alps is notably similar to the curve for the entire sample. This reflects the notion that glacier retreat on the century time scale is rather uniform over the globe. Around 1800, mean glacier length was decreasing and this decrease accelerated gradually. The present data set thus suggests that the Little Ice Age was at its maximum around 1800 rather than at the end of the 19th century as indicated by some other temperature proxies (M.E.Mann, P. D.Jones,Geophys. Res. Lett. 30, 10.1029/2003GL017814 (2003)).

2.7.8 Glacier Resources and Distribution

The Tibetan Plateau is the most concentrated glacier center in the middle and low latitudes on Earth, covering an area of 104,850km^2, including 23,000km^2 in India, 16,933 km^2 in Pakistan, 5322 km^2 in Nepal, and 49,873km^2 in China. The largest glacier cover is in the Himalayas, amounting to 34,660km2. The inventory of glaciers in China has identified 36,793 glaciers with an area of 49,873.44 km2, and ice volume of 4561.3857 km3 in the Tibetan Plateau of China (Table 2.2) (Liu Chaohai et al., 2000).

Table2.2: Glaciers area for different countries

Country	*Glacier area / km2*	*Sources*
China	49873	Liu Chaohai *et al.*, 2000
India	23000	Kulkarni, A. V. and Buch, A. M., 1991
Pakistan	16933	http://www.pakembwaw.com.pl/SeePakistan.htm
Nepal	5322	Bajracharya, S. R. *et al.*, 2002
Bhutan	**1318**	**Bajracharya, S. R. *et al.*, 2002**
Sikkim	912	Hasnain, S.I., 2000
Tajikistan	7493	Liu Chaohai *et al.*, 2000
Total	**104850**	

2.8 IMPACTS OF THE GLACIER MELT /RETREAT

Under the effects of the world wide glacier melting three central problems are closely described which might affect us in the future:

2.8.1 The rise in sea level

Between the 19th and the 20th Century the sea level rose by about 20 cm. Melting glaciers have a substantial part in this development with 1 cm here. In the year 2100 it is possible that the sea level will have increased by 20 to 60 cm.

2.8.2 The outbursts of glacial lakes

With the melting of the glaciers, rocks and boulders break off in areas with high relief energy for example the Alps. This rubble collects itself at the end of the glacier as moraines and forms a natural wall. The wall prevents the drain of the melt water, so that a glacier lake develops. If the water pressure grows too large, the wall can suddenly break, whereby large quantities of water are set free and catastrophic inundations are able to be caused.

2.8.3 Effect on water resources

There is growing concern about the impact that changes in glaciers may have on water resources in the riverhead regions. In the Baspa Glacier basin, the winter stream flow increased 75 percent since 1966, and local winter temperatures have warmed, which suggests that glaciers will continue to melt in future winters (Kulkarn *et al* 2004).

2.8.4 Lake area and river stream flow

The glaciers in the headwaters region have been retreating continuously since the 1980s, the recession rate of those in the Yellow River source region being larger than those of the Tianshan and Qilian Mountain regions. The glaciers in the Yangtze River source region, in comparison, are retreating at a relatively slow rate (Liu *et al.* 2002)

CHAPTER 3

STUDY AREA AND DATA DESCRIPTIONS

3.1 GENERAL

Bhutan is a small kingdom covering an area of 46,500 km^2 in the eastern part of the Himalayan Range. It is surrounded by the Tibetan Plateau in the north, the Bengal and Assam Plains in the south, Arunachal Pradesh in the east and the Darjeeling and the Sikkim Himalaya in the west.

Bhutan is mountainous with elevations ranging from 150 m up to 8,000 m. Three main ethnic groups live in Bhutan. Ngalops live in the northwestern region. Sharchops inhabit eastern and central region and Lhotshampas in the southern foothill districts. The economy, one of the world's smallest, is based on agriculture and forestry. About 70% of the population depends on agriculture for their livelihood. Agriculture consists mainly of subsistence farming and animal husbandry. Agriculture share to GDP is 36.4% in 2000. Bhutan's hydropower and tourism are key financial resources. The hydroelectricity power sector is the single biggest revenue earner of the Kingdom with hydro-electricity power potential of about 30,000 MW. Most of the rivers come from the glaciers and altitude difference provides huge potential for hydropower. Rugged terrain makes building of roads and other infrastructure difficult and expensive. Each economic program takes into account the people's desire to protect the country's environment and cultural traditions. Bhutan's economic growth climbed to 7.7% in 2002 from 6.6% the previous year.

3.1.1 Location of Bhutan

Figure 3.1: Location map of Bhutan

Land of Thunder Dragon (figure 3.1), some call it Last Shangrila and others still refer as Land of *Peaceful Dragon* are the terms used for this little kingdom of Bhutan nestled in the eastern part of the Great Himalayan Range. Located between the two giants of Asia, China in the north and India on the rest of the three sides lies between the following geographical coordinates 88°56'37.6"E & 92°14'27.6"E longitude and 26°40'19.18" N & 28°19'14.5"N latitude and populated with just over 700000 people.

3.1.2 Physical Features

Since the country is located in the Great Himalayas, the terrain is mostly rugged and mountainous with altitude ranging from less than 100 m in the south to more than 7500 m in the north within a north south distance of less than 175 Km. The area above 4200 m which is about 20.5 % of the total land area is permanently covered with snow and ice forming glaciers and glacial lakes.

3.1.3 Climate change in Bhutan

Is our climate really changing? If so, what are the expected impacts? What are the suitable adaptation methods to these impacts? And how capable are we to adapt ourselves to this changing climate?

These are few simple questions but very important that the scientist and researchers are posing in any major conference on climate change around the world. Numbers of global models were developed in relation to this topic and numbers of scenarios were developed from such models. But the bottom line is "Climate change and Global warming is unequivocal, as is now evident from observations of increase in global average air and ocean temperature, widespread melting of ice and snow and rising global sea level" (IPCC 2007).

GLOFs occur with regularity in the valleys and low lying river plains of Bhutan. In the recent past, flash floods have occurred in the Thimphu, Paro and Punankha-Wangdue valleys. Of the **2674** glacial lakes in Bhutan, **25** have been identified by a recent study as most dangerous to be considered for GLOFs in the near future. In October 1994, GLOF 90 kilometers upstream from Punakha Dzong caused massive flooding on the Pho Chhu River, damaging the dzong and causing casualties.

Shortage of water resources due to retreating and shrinkage of glaciers and hazards related to Glacial Lake Outburst Floods (GLOFs) are serious impacts felt among the communities residing in mountain environment from the changing climate. With the setting in of widely discussed and debated phenomena "the global warming" and considering the sensitivity of the mountain environment, especially the cryosphere to the ever rising air temperature, the consequence became more serious from the later half of this century.

In Bhutan due to the physiographic condition, major portion of the Bhutanese population are settled in the fertile valleys along some main river system. Should GLOF occur along these rivers which has their source from the glaciers and glacial lakes, the lives and property of these people are in danger which if struck will be a disaster. Such devastating effect can still be seen today from the last GLOF of 1994 along **Puna Tsang Chu.** Not only the lives and property are endangered but the important infrastructures such as the mega hydro power plant are located all along these major rivers. If Gross National Happiness (GNH) is the pride of Bhutanese people then the driving force behind it is these hydro power plants which are driving the Bhutanese economy ahead with a contribution of about 45 % to the national revenue and 12% to GDP growth (ADB Review 2005).

Realizing such eminent impact from the climate change, the Royal Government of Bhutan has taken a step further in the process of adaptation to climate change by developing the National Adaptation Program of Action (NAPA), which has been coordinated by the National Environment Commission (NEC). The main objective of NAPA was to identify and address the most prominent issues related to climate change. During the NAPA formulation three projects from the department of Geology and Mines (Artificial lowering of lake water level in Thorthormi lakes, Installation of early warning system in Punakha-Wangdi valley and hazard zonation in chamkhar) were prioritized in the nine important projects keeping in mind the severe effect of climate change on the glaciers and glacial lakes in Bhutan. Our present project "Hazard zonation map for GLOF along Puna Tsang Chu from Khuruthang to Lhamoizingkha" though not listed under NAPA projects but the department felt it to be of utmost importance owing to the following reasons. The Hazard zonation map from Lunana (source) till Khuruthang in Punakha was done through Austro-Bhutan Project.

a. Historical monuments and settlements are concentrated along this river basin.

c. Number of mega hydro power plants which are in pipeline lie on Puna Tsang Chu.

d. The earlier studies with the Austrians and Japanese researchers shows that lakes in Lunana still has GLOF potential and hazard zonation was one of the means recommended by them.

Southwestern monsoon originating from the Bay of Bengal dominates the climate in Bhutan. Normally the monsoon sets in the mainland by early June and last till early September. Just after the monsoon during the month of October and November occasional rains occur, which is basically the post monsoon rains and can be quite severe. From November to March the period is usually dry but sometimes light showers may occur from the westerly winds which brings rain in the foothills of the Himalayan range. The pre-monsoon season falls in the month of April and May which are accompanied by light showers, lightning and hailstorm. The record shows a rainfall of approximately 2500-5500 mm in southern foothills, 1000-2500 mm in the inner valleys and 500-1000 mm in the northern flank of the country. Climatically the country can be divided into three zones namely the following.

a. Subtropical in the southern foothills
b. Temperate in the middle or inner valleys
c. Alpine in the northern part

All four seasons can be experienced in the country characterized by hot and humid in the southern foothills during summer and cool in winter, the middle valleys are warm in summer and cold in winter with pleasant spring and autumn with mild temperatures. Overall the variation in the climate is dominated by the altitudinal change.

3.1.4 River System of Bhutan

Most of the rivers in Bhutan flow from north to south. The country is drained by five major river systems namely Amo Chu, Wang Chu, Puna Tsang Chu or Sunkosh and Manas and Nyere Ama Chu with many tributaries which are of appreciable size. Except for Amo Chu and Nyre Ama Chu the rest three major rivers are formed by joining number of tributaries. Wang Chu is a collection of three main tributaries namely Pa Chu, Ha Chu and Thim Chu. Puna Tsang Chu or Sunkosh is formed by collection of another three main tributaries namely Pho Chu, Mo Chu and Dang Chu. Similarly the Manas river system is a collection of another four major tributaries i.e Mangde Chu, Chamkhar Chu, Kuri Chu and Dangme Chu. Almost all these rivers have their source from the perpetual snow and ice in the northern frontier of the country except for Kuri Chu which is a transboundry river having its source in China.

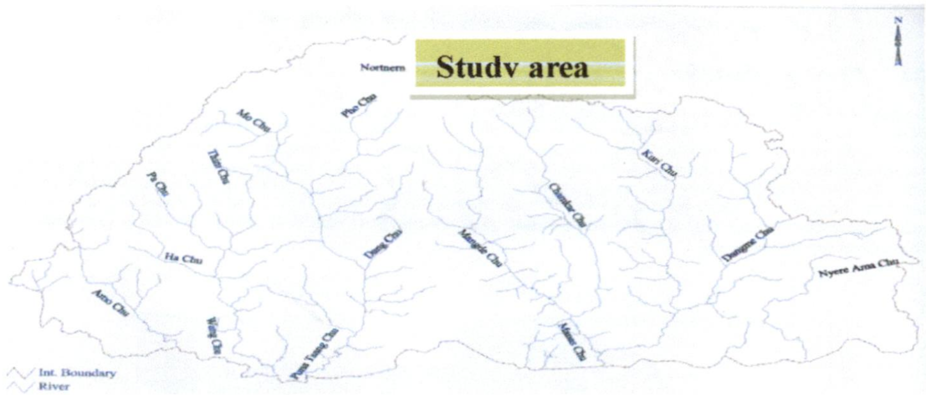


Fig 3.2: River system of Bhutan

3.2 STUDY AREA

3.2.1 Lunana Glacial Lakes

Lunana region is situated at the latitude of 28°05'30.20" and longitude of 90°11'33.56" in the northern part of country at the 4352 m a.m.s.l. Mostly the northern part of Bhutan is covered with snow throughout the year and also have glacier coverage

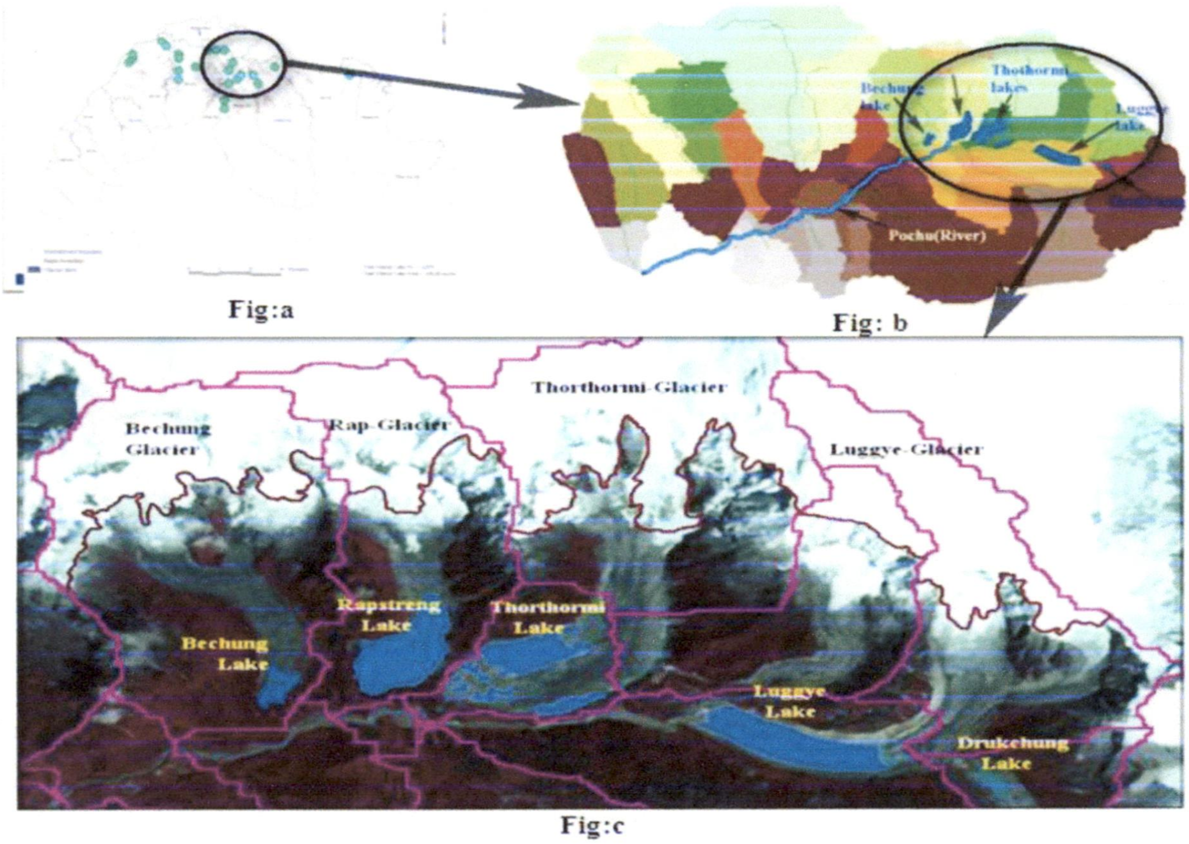


Fig 3.3: a) Location of the Study area in Bhutan; b) Watershed of study area; c) location of Glaciers and Glacial lakes in study area.

Covering an area of 1,317 square kilometers most of the 677 known glaciers in Bhutan have spawned "many dangerous moraine-dammed lakes" which are "increasing in size at a very fast rate" but study area itself is around 437km^2(Figure 3.3b).

These natural dams may, because of huge amount of accumulated water, suddenly break like the Luggye Tsho that caused the Punakha flood, discharging large volumes of water and debris. Some glaciers are retreating by about 20 meters to 30 meters every year.

While most of the lakes that lie in the Lunana region do not pose an immediate threat, two glacial lakes, **Raphstreng Tsho and Thorthormi (Thortomi) Tsho**, both at the source of the **Pho Chhu**, are considered risky, with the latter predicted to burst in 15 to 20 years.The findings were made by numerous expeditions in the Lunana area after the **1994** flood (YUTAKA AGETA, *Autumn 1998*)

3.2.2 Luggye Tsho (Lake) and Drukchung Tsho (lake)

Lake Luggye Tsho is an end **moraine-dammed lake in the Pho Chu** basin of the Lunana region. As late as the 1950s, there were no indications of any lakes being associated with Luggye glacier. The first lake appeared only in 1967 (Gansser, 1970) as a supraglacial lake and was measured to be 0.02 sq.km in 1968.The depth of Luggye Lake was measured in 2000 and shown to be 142m. This glacial lake suffered an outburst event on 7th October 1994.

The GLOF from Lake Luggye Tsho caused much damage to the downstream valley, including the religiously important Punakha Dzong. After the breach, the lake continued to grow towards the glacier snout and the glacier continued to retreat; in 2001 the lake area measured 1.12sq.km.The exposure of ice cliffs on the glacier snout show calving, which contributes to the expansion of the lake towards the glacier. The outlet channel is at the same level as the lake surface and has a gentle slope. Evidenced by its bumpy topography, this terminal moraine has an ice core. Both the continuous sliding of the left lateral moraine at the outlet and the presence of an ice core contribute to the possibility of blocking of the previously breached outlet so that the lake could at some time in the future suffer another GLOF event.

If the outlet of Lake Luggye Tso is blocked by landslides from the left lateral moraine it will cause the water level of the lake to rise, risking a GLOF event with serious consequences for the Thorthormi lakes further downstream, especially since the Thorthormi glacier has already weakened the left lateral moraine (Ageta et al, 2000). Austrian experts Leber and Hausler (2002) concur about the risk from Lake Luggye Tso.

In fact, of the possible scenarios that this group examined during their risk assessment of the Luggye GLOF, the blockage of the outlet by a landslide from the left lateral moraine was considered the "major risk" (Leber and Hausler, 2002). This group recommended that the active sliding zone on the left lateral moraine be stabilised at the outlet to allow free flow of water from the lake. In contrast, Dorji (1996) observed no immediate GLOF risk from this lake because of its wide outlet channel. He commented that the risk of flood from this lake is not imminent as the outlet channel is wide enough to discharge any amount of water that will accumulate.

In the 1950s, there were no significant lakes on either Lugge Glacier or Drukchung Glacier which joins Luggye Glacier from the southeast. According to Gansser's observation in 1967, many supraglacial ponds had formed on both glaciers; he found clear signs of recent drainage of ponds on Drukchung Glacier (Gansser, 1970).

3.2.3 Rapstreng Tsho (Lake)

Lake Raphstreng Tsho lies at an altitude of 4360m. This lake appeared as a supraglacial lake in a 1958 topographic map; topographic maps from 1960 showed that the lake's area was 0.15 sq.km. In 1986 it was 1.65 km long, 0.96 km wide and 80m deep (Sharma et. al., 1986). Nine years later, the Indo-Bhutan Expedition of 1995 measured a maximum length of 1.94 km, width of 1.13 km, and depth of 107m (Ageta et al., 2000).

The depth measured in 1999 was about 100m. Some researchers believe that the lake's present dimensions represent its maximum since the upstream section has already reached the bedrock wall. However, field photographs show that the glacier snout is undergoing extensive calving and that the lake can still expand a few hundred more metres. Prior to the 1994 flood from Lake Luggye Tsho, the left lateral moraine was 295 to 410m wide (Bhargava 1995). Toe erosion of the moraine initiated by the flood has reduced the width to 178m. This weakening of the lake barrier and the large size of the lake caused grave concern to the Government of Bhutan. An immediate investigation of the stability of the lake was undertaken in 1995. Three phases of mitigation work were carried out on this lake from 1996 to 1998 in an attempt to lower the water level by about 4m. A channel of 78.5m in length and 36m wide at the outlet was manually widened and deepened at the lake outlet. Nevertheless, the risk of a GLOF cannot be ruled out because a large volume of water is still stored in the lake and a chain effect of GLOFs from other adjacent lakes could occur. An additional threat to the stability of Lake Raphstreng Tsho comes from hydrostatic pressure exerted by the Thorthormi lakes, from which Lake Raphstreng Tsho is separated by only a moraine wall.

3.2.4 Thorthormi Tsho (Lake)

Of the 14 risky glacial lakes in Lunana, Lake Thorthormi is on the brink of breaching its walls. Geology department say they are working on it. Lake Thorthormi is the largest glacial lakes in Bhutan, with a size of 3.42 sq. km, and thrice the dimension of Lake Lugge that burst in 1994. Geologists say the massive ice surrounding Lake Thorthormi is melting fast at 30-35 metres a year, and is filling up the lake quick. The natural dam holding the lake can stand only so much volume of water, say geologist. Lake Thorthormi feeds Punakha Pho Chhu and if it bursts, geologist say, it could inflict enormous damage downstream. Lake Luggye when it ruptured flooded villages on the way including Punakha town killing 22 people and uncountable livestock. Lake Thorthormi is thrice the size of Lake Luggye.

A glacial expert, Dr Yeshi Dorji, of the geology department, said that measures were being planned and beyond to reduce the water level of Lake Thorthormi and establish early warning system for the communities downstream.

3.2.5 Bechung Tsho (Lake)

Bechung Tsho (lake), (28°06'07.08"N, 90°13'50.52"E) at an elevation of 4335 m m.a.s.l is situated just beside the Rapstreng Lake. It had no significance in the map of 1990s and in 2001; it appeared with very small in size in late 1990s. Initially it was only one in 2001 and became two in 2007 and again merged into one in 2009 (*by GIS digitization*)

3.3 POTENTIAL DANGEROUS GLACIAL LAKES.

In addition to identifying and classifying glaciers and glacial lakes, ICIMOD Survey has also identified potentially dangerous glacial lakes with a view to estimate likely glacial lake outburst hazards. The criteria for identifying potentially dangerous glacial lakes are based on field observations, processes and records of past events, geo-morphological and geo-technical characteristics of the lake and surroundings, and other physical conditions. From the ICIMOD Survey, 24 glacial lakes have been identified as potentially dangerous in Bhutan on the basis of analysis of data using different criteria and the study of topographic maps and satellite images.

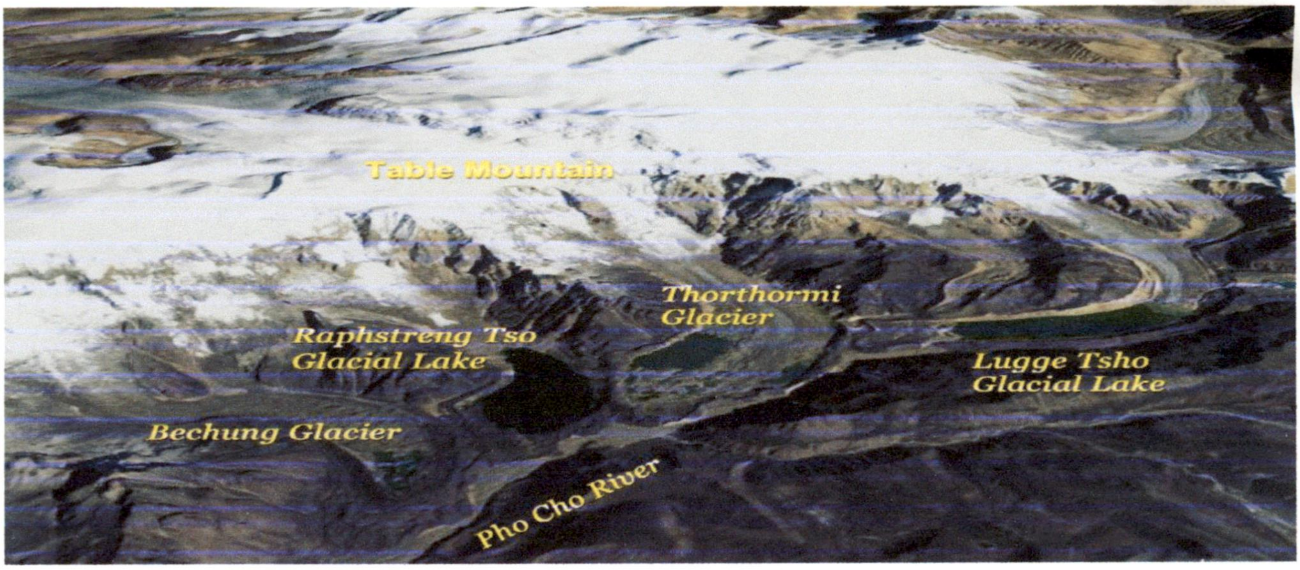


Fig 3.4: Potential Glacial Lakes in the study area

Out of these, there are 5 potentially dangerous glacial lakes in Mo Chu sub-basin and 8 glacial lakes in Pho Chu sub-basin but four of them are most dangerous Lakes at this present secenerio. The details of these main glacial lakes in Pochu river basin are given below in Table-3.1

Table-3.1: Potentially dangerous glacial lakes in Pho Chu subbasin

Sl.No	Lake No.	Name	Latitude	Longitude
1	Pho_gl	Thorthormi	28°6'49.48"N	90°16'52.09"E
2	Pho_gl	Bechung	28°7'39.92"N	90°13'16.03"E
3	Pho_gl 163	Not given	28°06'06.43"N	89°54'11.83"E
4	Pho_gl 164	Tarina	28°06'37.22"N	89°54'37.81"E
5	Pho_gl 209	Raphstreng	28°06'43.56"N	90°14'03.65"E
6	Pho_gl 210	Luggye	28°05'00.34"N	90°18'28.58"E
8	Pho_gl	Drukchung	28'05'12.34"N	90'19'34.14"E

3.4 DATA DESCRIPTIONS

3.4.1 Hydrological data

These are the data that were extracted from the Land sat maps for different years of 1990, 2001, 2007 and 2009. These Lakes are located at one of the River called Pochu and the area are obtained from Land sat maps for different years. So due to the Global warming, the areas of the Lakes seem to be increasing at consistent rate and the details as found from the Land sat map by digitizing using ArcGIS 9.3 of these lakes for different time period are given in Table 3.2

Table 3.2. Area and perimeter of the Glacial Lakes for different years

(Source: ArcGIS 9.3 Digitization)

		Location			Area		Perimeter	
Year	Name of Lakes	Latitude	Longitude	Elevat-ion(m)	m2	Km2	m	Km
1990	Rapstreng	28'06'24.01"N	90'14'51.76"E	4368	1135073.4	1.14	4750.1	4.8
	Thorthormi_1	28'06'21.78"N	90'15'48.95"E	4454	37097.5	0.04	1404.7	1.4
	Thorthormi_2	28'06'15.23N	90'15'21.95"E	4459	18700.5	0.02	872.8	0.9
	Thorthormi_3	28'06'06.66"N	90'15'25.61"E	4462	31396.8	0.03	1290.5	1.3
	Thorthormi_4	28'05'52.78"N	90'16'05.16"E	4461	111609.8	0.11	2155.8	2.2
	Luggye	28'06'02.13"N	90'15'18.08"E	4459	978421.2	0.98	4997.8	5.0
	Drukchung	28'05'12.34"N	90'19'34.14"E	4706	135733.0	0.14	2218.5	2.2
2001	Bechung	28'06'07.64"N	90'13'49..51"E	4337	64049.8	0.06	2402.4	2.4
	Rapstreng	28'06'24.01"N	90'14'51.76"E	4368	1173815.3	1.17	5124.8	5.1
	Thorthormi_1	28'06'21.78"N	90'15'48.95"E	4454	335744.8	0.34	2880.5	2.9
	Thorthormi_2	28'06'15.23N	90'15'21.95"E	4459	49708.6	0.05	1385.5	1.4
	Thorthormi_3	28'06'06.66"N	90'15'25.61"E	4462	38185.1	0.04	1338.6	1.3
	Thorthormi_4	28'05'52.78"N	90'16'05.16"E	4461	136944.8	0.14	2199.1	2.2
	Thorthormi_5	28'0602.13"N	90'15'18.08"E	4459	47466.4	0.05	1560.9	1.6
	Luggye	28'06'02.13"N	90'15'18.08"E	4459	1158984.8	1.16	5599.0	5.6
	Drukchung	28'05'12.34"N	90'19'34.14"E	4706	121970.5	0.12	2299.6	2.3
2007	Bechung	28'06'07.64"N	90'13'49..51"E	4337	111317.6	0.11	2420.6	2.4
	Bechung_1	28'06'00.17"N	90'13'48.25"E	4336	39754.7	0.04	1421.8	1.4
	Rapstreng	28'06'24.01"N	90'14'51.76"E	4368	1225310.5	1.23	5415.0	5.4
	Thorthormi_1	28'06'21.78"N	90'15'48.95"E	4454	651363.3	0.65	5183.8	5.2
	Thorthormi_2	28'06'15.23N	90'15'21.95"E	4459	57802.6	0.06	1601.6	1.6
	Thorthormi_3	28'06'06.66"N	90'15'25.61"E	4462	79103.2	0.08	2026.3	2.0
	Thorthormi_4	28'0602.13"N	90'15'18.08"E	4459	144131.1	0.14	2233.4	2.2
	Thorthormi_5	28'05'52.78"N	90'16'05.16"E	4461	48020.9	0.05	1595.9	1.6
	Luggye	28'06'02.13"N	90'15'18.08"E	4459	1261337.2	1.26	6292.9	6.3
	Drukchung	28'05'12.34"N	90'19'34.14"E	4706	112251.0	0.11	2170.6	2.2
2009	Bechung	28'06'07.64"N	90'13'49..51"E	4337	172287.9	0.17	3378.4	3.4
	Rapstreng	28'06'24.01"N	90'14'51.76"E	4368	1254513.8	1.25	6060.5	6.1
	Thorthormi_1	28'06'21.78"N	90'15'48.95"E	4454	164990.0	0.16	2669.7	2.7
	Thorthormi_2	28'06'15.23N	90'15'21.95"E	4459	77710.0	0.08	1839.2	1.8
	Thorthormi_3	28'06'06.66"N	90'15'25.61"E	4462	96807.6	0.10	2397.4	2.4
	Thorthormi_4	28'05'52.78"N	90'16'05.16"E	4461	128055.5	0.13	2952.3	3.0
	Thorthormi_5	28'0602.13"N	90'15'18.08"E	4459	71806.0	0.07	2229.5	2.2
	Luggye	28'06'02.13"N	90'15'18.08"E	4459	1412751.1	1.41	8329.8	8.3
	Drukchung	28'05'12.34"N	90'19'34.14"E	4706	115490.6	0.12	2297.4	2.3

3.4.2 Meteorological Data

To study the trend analysis for the temperature and rainfall of Bhutan at present scenario, the daily temperature and daily precipitation were collected from one of the stations called

Meteorology Section, Hydro met Services Division, Department of Energy, MTI, Thimphu, Bhutan, nearest to Lakes. Data are minimum rainfall (mm), maximum rainfall (mm), minimum temperature, maximum temperature (°C) and the average data for the both rainfall (mm) and temperature (°C) have been collected (Figure 3.5 and Figure 3.6)

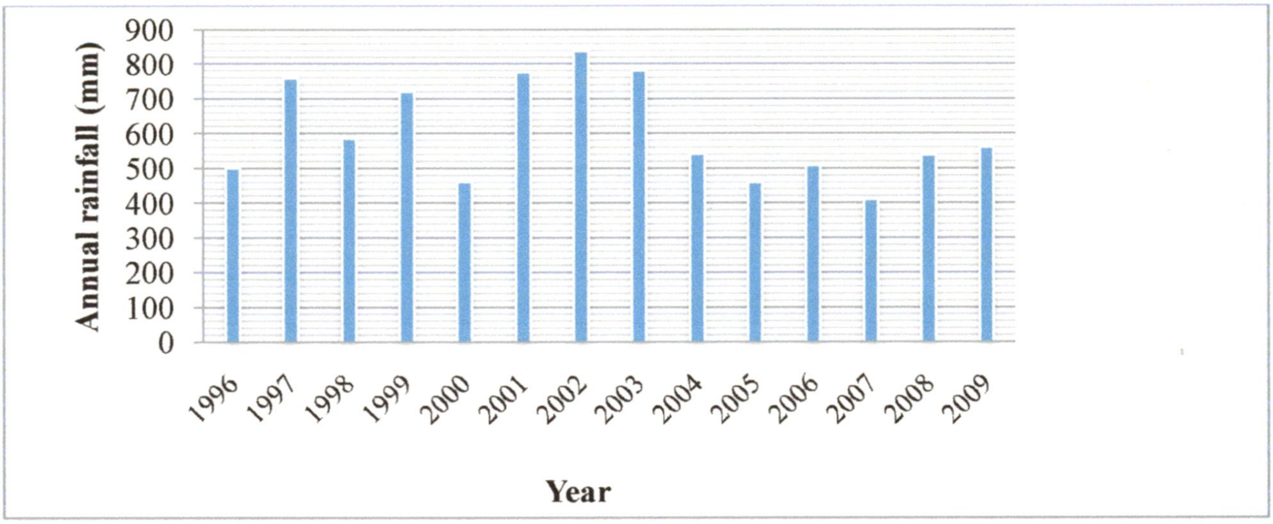


Fig 3.5: Annual rainfall

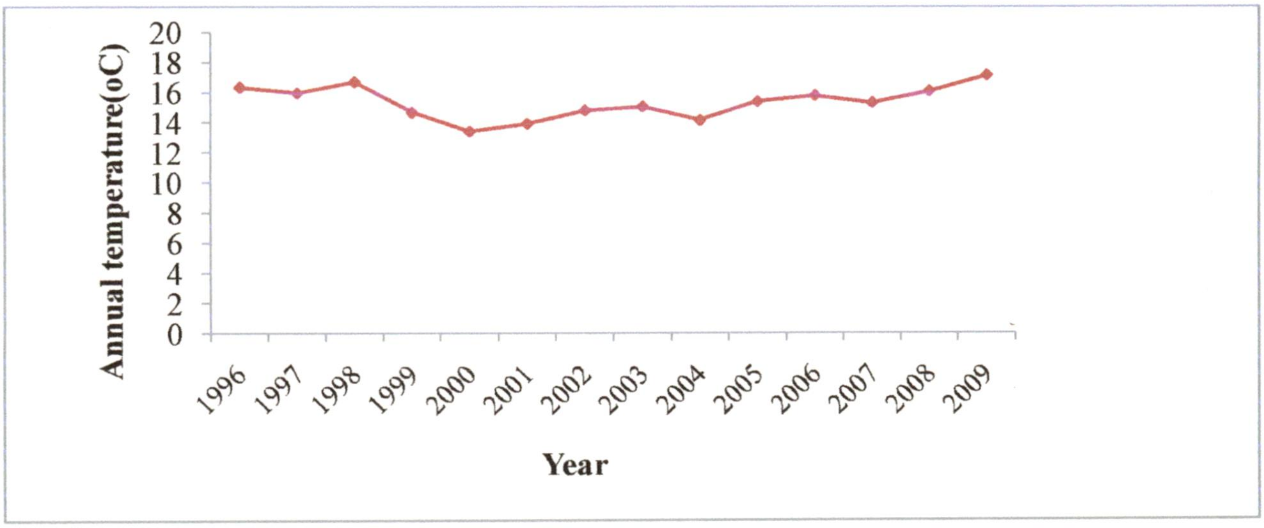


Fig 3.6 Annual mean temperatures

CHAPTER 4

METHODOLOGY

4.1 GENERAL

The methodology for present study is divided into three divisions as shown in flow chart (Figure: 4.1). The first step is to review "*Climate Change*" using statistical method to evaluate the patterns of the climate that has been exhibited in the past in order to determine the present as well as future. The second step is "*The assessment of Glaciers retreat and Glacial lakes expansion*" using GIS in order to determine the Retreat Rate of Glaciers. The third step is to "*model the glacial lakes*" using HEC-RAS in order to perform an unsteady flow analysis and also watershed delineation by Arc Hydro tool to find out the study area. It also determines the nature of flood propagation at the downstream of the rivers (Figure 4.1)

4.2 MANN-KENDALL ANALYSIS

The Mann-Kendall test was performed to evaluate the trend of precipitations at rain gauge stations. Using statistical methods, the determination of temporal trends and their spatial distribution of historical, annual and seasonal precipitation and temperature series in Lunana region and Gasa region is necessary. The Mann-Kendall test is a non-parametric test for identifying trends in time series data.

4.2.1 CALCULATION OF THE MANN-KENDALL STATISTIC (S)

Mann-kendall (MK) test.

The magnitude of the trend in the seasonal and annual series was determined using the Sen's estimator (Sen, 1968) and statistical significance of the trend in the time series was analyzed using Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975).

Magnitude of trend

The magnitude of trend in a time series was determined using a non-parametric method known as Sen's estimator (Sen, 1968). This method assumes a linear trend in the time series. In this method, the slopes (T_i) of all data pairs are first calculated by

$$T_i = \frac{x_j - x_k}{j - k} \qquad \text{for } i = 1,2,\ldots\ldots.,N \qquad (4.1)$$

where x_j and x_k are data values at time j and k (j>k) respectively. The median of these N values of T_i is Sen's estimator of slope which is calculated as

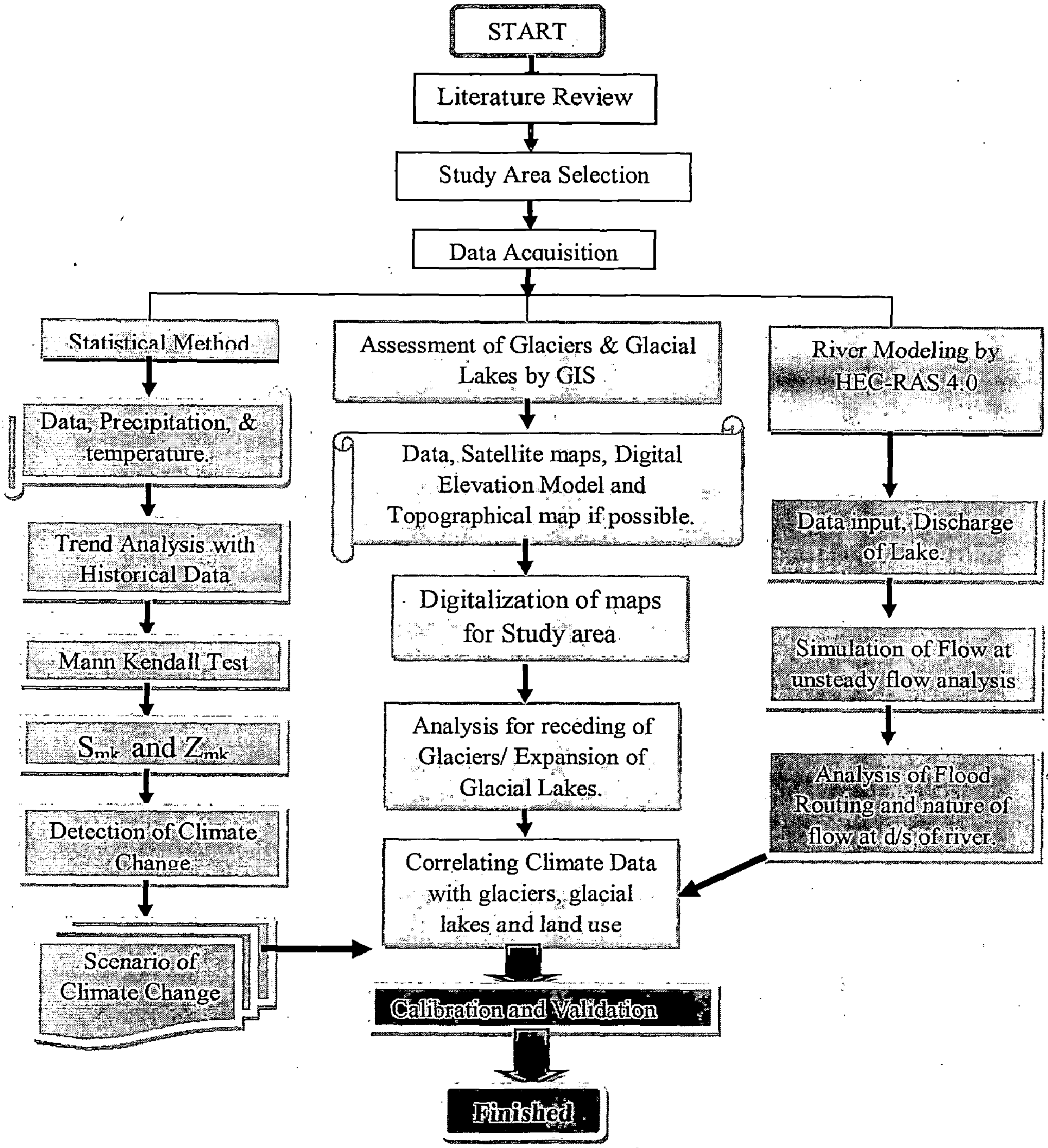


Fig 4.1: Flow Chart of Methodology

$$Qi = \begin{cases} T_{\frac{N+1}{2}} & N \text{ is odd} \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) & N \text{ is even} \end{cases} \tag{4.2}$$

A positive value of Q_i indicates an upward (increasing) trend and a negative value indicates a downward (decreasing) trend in the time series.

Significance of trend

To ascertain the presence of statistically significant trend in hydrologic climatic variables such as temperature, precipitation and stream flow with reference to climate change, nonparametric Mann-Kendall (MK) test has been employed by a number of researchers (Douglas et al., 2000; Yue et al., 2003; Burn et al., 2004; Singh et al., 2008a, b; Kumar et al., 2009). The MK method searches for a trend in a time series without specifying whether the trend is linear or non-linear. In the present study the MK test was also applied. MK test checks the null hypothesis of no trend versus the alternative hypothesis of the existence of increasing or decreasing trend.

The statistics (S) is defined as (Salas, 1993)

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \text{sgn}(x_j - x_i) \tag{4.3}$$

Where N is number of data points. Assuming $(x_j\text{-}x_i) = \theta$, the value of $sgn(\theta)$ is computed as follows:

$$\text{sgn}(\theta) = \begin{cases} 1 & if \quad \theta > 0 \\ 0 & if \quad \theta = 0 \\ -1 & if \quad \theta < 0 \end{cases} \tag{4.4}$$

This statistics represents the number of positive differences minus the number of negative differences for all the differences considered. For large samples (N>10), the test is conducted using a normal distribution (Helsel and Hirsch, 1992) with the mean and the variance as follows:

$$\text{E[S]} = 0 \tag{4.5}$$

$$Var(S) = \frac{N(N-1)(2N+5) - \sum_{k=1}^{n} t_k(t_k - 1)(2t_k + 5)}{18} \tag{4.6}$$

where n is the number of tied (zero difference between compared values) groups, and t_k is the number of data points in the k_{th} tied group. The standard normal deviate (Z-statistics) is then computed as (Hirsch et al., 1993):

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if \quad S < 0 \end{cases} \tag{4.7}$$

If the computed value of $|Z| > z_{\alpha/2}$, the null hypothesis (H_o) is rejected at α level of significance in a two-sided test. In this analysis, the null hypothesis was tested at 95% confidence level.

4.3 GEOGRAHIC INFORMATION SYSTEM (GIS)

One of the main objectives of the present study is to develop a digital database of glaciers and glacial lakes using geographic information systems (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 attributes 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 can be found in Arnoff (1989).

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, centers 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.

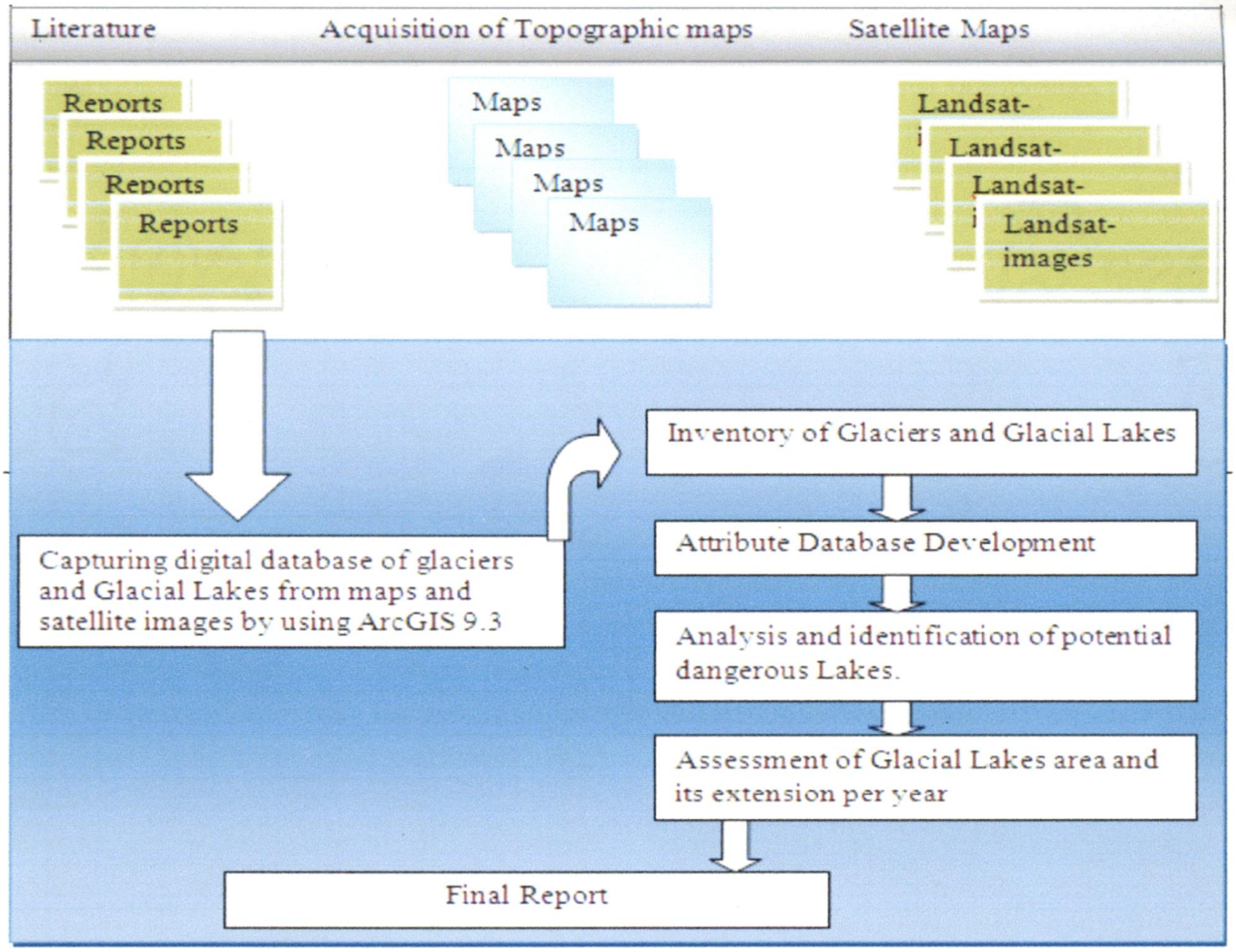


Fig 4.2: The flow diagram of methodology used for inventory

Most of the attributes were derived from the topographic maps, aerial photographs, satellite images, reports, field data, etc. Attributes such as area, location (latitude, longitude) etc 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 etc as measuring units for glaciers and glacial lakes. Other attributes such as aspect, mean length, elevation, map code, name, etc, were manually entered in the attribute database. Additional attributes, such as mean elevation, volume etc were derived using logical calculations. For each basin, attribute tables were developed for glaciers and glacial lakes. 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, etc.(Figure 4.2)

4.3.1 Satellite data

Various satellite images of different years of 1990, 2001, 2007 and 2009 are taken for present study. For the watershed delineation ASTER DEM and SRTM DEM are used and some of the SPOT images are also used to see the variation of Glaciers and Glacial Lakes (Table 4.1).

Table 4.1: Details features of images.

Sl.No.	Satellite images	Sensor type	Acquired Date	Resolution
1	Landsat	TM	14.11.1990	30m
2	Landsat	TM	20.11.2001	30m
3	Landsat	TM	23.12.2007	30m
4	Landsat	TM	20.10.2009	30m
5	Spot-5 images	-	25.11.2009	10m

4.3.2 Inventory of Glacial Lakes

The climate changes condition have had an impact on the high mountain glacial environment. Many of big Glaciers have melted rapidly and given birth to number of new glacial lakes. Due to the rapid rate of ice and snow melt, possibly caused by global warming, the accumulation of these lakes has been increasing rapidly. The isolated lakes above 3,500 m above m.s.l are assumed to be a part of the glacial lakes left due to the retreat of the glaciers.

4.3.3 Area and Perimeter of Glacial Lakes

The area and perimeter of Glacial Lakes are determined from the digital data base after digitization of the Lakes from the Satellite Images. Using the three different images, there was some changes in area and perimeter which means there is an increasing in both the parameters. Area of glaciers of the study area of watershed are found out from the Land use land cover mapping from the ERDAS for different years to observe the changes in due course of time.

4.3.4 Area of the glaciers

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 kilometers and delineated glaciers are digitized in GIS and data base is used to calculate the total area.

4.3.5 Elevation of the glaciers

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 glaciers elevation), and lowest elevation (elevation of the glacier tongue).

4.3.6 Mean Glaciers thickness and ice reserves

There is no measurement for glacial ice thickness for the Bhutan Himalayas. Measurement of glacial thickness in the Tianshan Mountains, China, show that the glacial thickness increases with the increase of its area (LIGG/WECS/NEA 1988). Since the mean thickness of glaciers data were not available, the relationship between ice thickness (H) and glacial area (F) was obtained as below (Cahohai Liu and Liangfu 1986)

$$\mathbf{H=-11.32+53.21F^{0.3}} \qquad (4.8)$$

Where H=mean thickness (m) and F=area of Glacier (Km^2). The ice reserves were estimated by multiplying the thickness by the area of the glaciers. So this formula has been used to estimate the mean ice thickness in the glacier inventory of the Arun and Bhote-Suntoshi Basin of Nepal. The same method is used here to find the ice thickness.

Muller et al. (1977) roughly estimated the ice thickness values for Khumbu Valley in Nepal using the relationship between glacier type, form, and area. This method was used by WECS to calculate the thickness values for Rolwaling Valley in Nepal.

4.3.7 Volume of Glacial Lakes

There is no estimate available for volume of glacial lakes in Bhutan from their water spread areas. However, some estimates are available for glacial lakes in Swiss Alps, as given by Huggel et al. ,(2002). In the absence of information on the volume of potentially dangerous glacial lakes in Bhutan, it is considered appropriate to use the same relationships developed for the lakes in Swiss Alps for estimating the water volume for the lakes on Pho Chu and Mo Chu sub-basins. The empirical relationships as available in the study by Huggel et al. (2002) are:

The lake volume(V)= $0.104\,A^{1.42}$ (4.9)

where V is the lake volume in m^3 *A is the lake area in* m^2.

The volume of potentially dangerous lakes on Pho Chu sub basin were accordingly estimated and given in next chapter and its rate of growing per year.

4.3.8 Surge Propagation (discharge calculation)

As GLOFs pose severe threats to human, man-made structures, agriculture fields and natural vegetation, it is important to make accurate estimates of the magnitude of future floods. Several methods have been devised to predict peak discharges, which are the most erosive and destructive phase of floods. The surge propagation hydrograph depends upon the type of GLOF event, i:e from moraine-dammed lakes or from ice dammed lake. The duration of a surge wave from 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 is usually higher than from ice- dammed lakes.

Clague and Mathews (1973) reviewed the literature concerning the maximum discharge of outburst floods (Qmax in m3 S^{-1}) and defined a scale relation with lake volume drained (*V* in $m^3 \times 10^{-6}$) as an explanatory variable. Recently, several modifications to the Clague-Mathews formula have been used (Jones and others, 1985; Costa, 1988) so as to include observations from more recent events and to exclude the Glacial Lake Missoula datum which represents a late Pleistocene event where there were several orders of magnitude larger than all other floods used to define the relation. This form of the relation was proposed by Costa (1988). The following methods have been proposed for estimation of ***peak discharges***:

a) 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.

$$Q_{max}=75(Vo*10^{-6})^{0.67} \quad (4.10)$$

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

$$Q_{max}=133(V_O*10^{-6})^{0.67} \quad (4.11)$$

Later Desloges et al. (1989) proposed:

$$Q_{max}=179(Vo*10^{-6})^{0.67} \quad (4.12)$$

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

4.4 Land Cover Mapping

4.4.1 Land Cover Class: The satellite images are obtained for 1990, 2001, 2007 and 2009 which are classified. The land use is classified in following different classes and their features are given below.

a) **Forest land**: Area with density of trees which include both deciduous and conifers forest and those trees are of mainly of high land tress of short height plants.

b) **Grass Land**: Area covered with grass and bushes.

c) **Glaciers**: Land or mountains covered with snows which have been covered throughout the year.

d) **Streams**: Small rivers or Streams which are being mainly sourced by melting of Glaciers and snow.

e) **Rivers**: Combination of those small streams.

f) **Glacial Lakes**: lakes of both types, ice dammed- lakes and the moraine dammed lakes.

g) **Barren Land:** Land with rock exposed, without vegetation and sandy soil etc.

4.4.2 Image Classification

Classification is the process of sorting pixels into a finite number of individual classes, or categories of data, based on their data file values. If a pixel satisfies a certain set of criteria, then the pixel is assigned to the class that corresponds to those criteria.

Image classification is a mean to convert spectral raster data into a finite set of classifications that represent the surface types seen in the imagery. These may be used to identify vegetation types, Glaciers, Glacial Lakes, anthropogenic structures, mineral resources, or transient changes in any of these properties. Additionally, the classified raster image can be converted to vector features (e.g. polygons) in order to compare with other data sets or to calculate spatial attributes (e.g. area, perimeter).

Image classification is conducted in three modes: supervised, unsupervised, and hybrid. In general, a supervised classification requires the manual identification of known surface features within the imagery and then uses a statistical package to determine the spectral signature of the identified feature. The "spectral fingerprints" of the identified features are then used to classify the rest of the image. This utility allows one to perform a supervised classification on an .img file using various decision rules. This utility can also be accessed from the Signature Editor. The ERDAS IMAGINE Signature Editor allows you to create, manage, evaluate, edit, and classify signatures (.sig extension). The following types of signatures can be defined:

- Parametric (statistical)
- Nonparametric (feature space)

In order to create signatures, one must have the image for classifying which opened in a Viewer. Then, using the AOI tools, one can create point, line, polygon, and "seed" areas of interest.

An unsupervised classification scheme uses spatial statistics (e.g. the ISODATA algorithm) to classify the image into a predetermined number of categories (classes). These classes are statistically significant within the imagery, but may not represent actual surface features of interest. Hybrid classification uses both techniques to make the process more efficient and accurate.

The supervised classification is the essential tool used for extracting quantitative information from remotely sensed image data [Richards, 1993, p85]. Using this method, the analyst has available sufficient known pixels to generate representative parameters for each class of interest. This step is called training. Once trained, the classifier is then used to attach labels to all the image pixels according to the trained parameters. The most commonly used supervised classification is maximum likelihood classification (MLC), which assumes that each spectral class can be described by a multivariate normal distribution. Therefore, MCL takes advantage of both the mean vectors and the multivariate spreads of each class, and can identify those elongated classes. However, the effectiveness of maximum likelihood classification depends on reasonably accurate estimation of the mean vector m and the covariance matrix for each spectral class data [Richards, 1993, p189].

4.5 Elevation

A topographical map is the main type of map used to depict elevation, often through use of contour lines. In a Geographic Information System (GIS), digital elevation models (DEM) are commonly used to represent the surface (topography) of a place, through a raster (grid) dataset of elevations. Digital terrain models are another way to represent terrain in GIS.

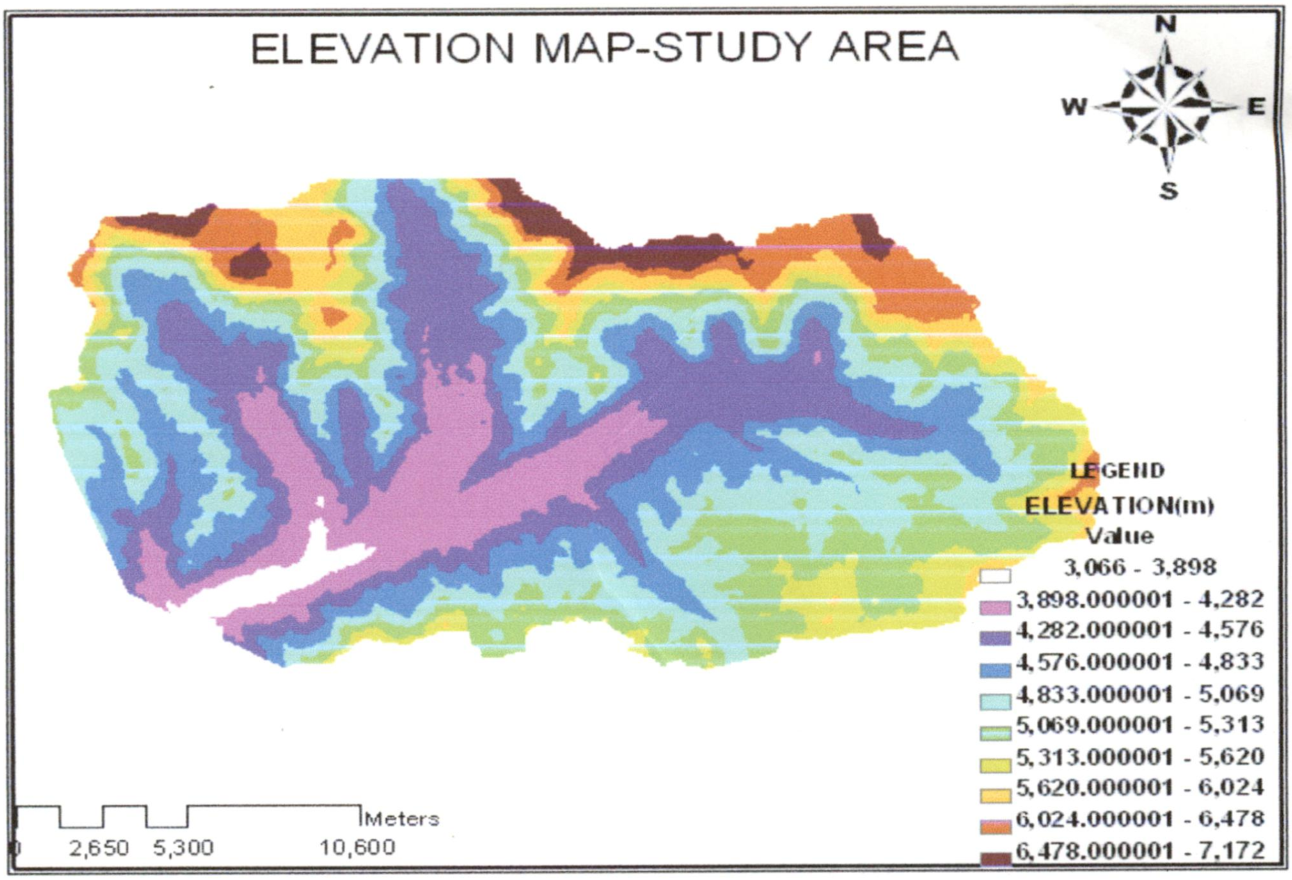


Fig 4.3: Elevation of study area.

Elevation difference between adjacent contour lines, called the contour interval, is selected to best show the general shape of the terrain. A map of a relatively flat area may have a contour interval of 10 m or more (Figure 4.3)

4.6 HEC-GeoRAS

4.6.1 General: HEC-GeoRAS is the set of procedures, tools and utilities for processing geospatial data in ArcGIS. The HEC-GeoRAS assists in preparation of geometric data to import into the HEC-RAS and processed simulation resulted is exported from the HEC-RAS. The layers created will be of cross sections and longitudinal-sections and main channels and the only essential dataset required for HEC-GeoRAS is the terrain data (TIN or DEM). The overall view of the GeoRAS diagram is shown in Figure 4.4.

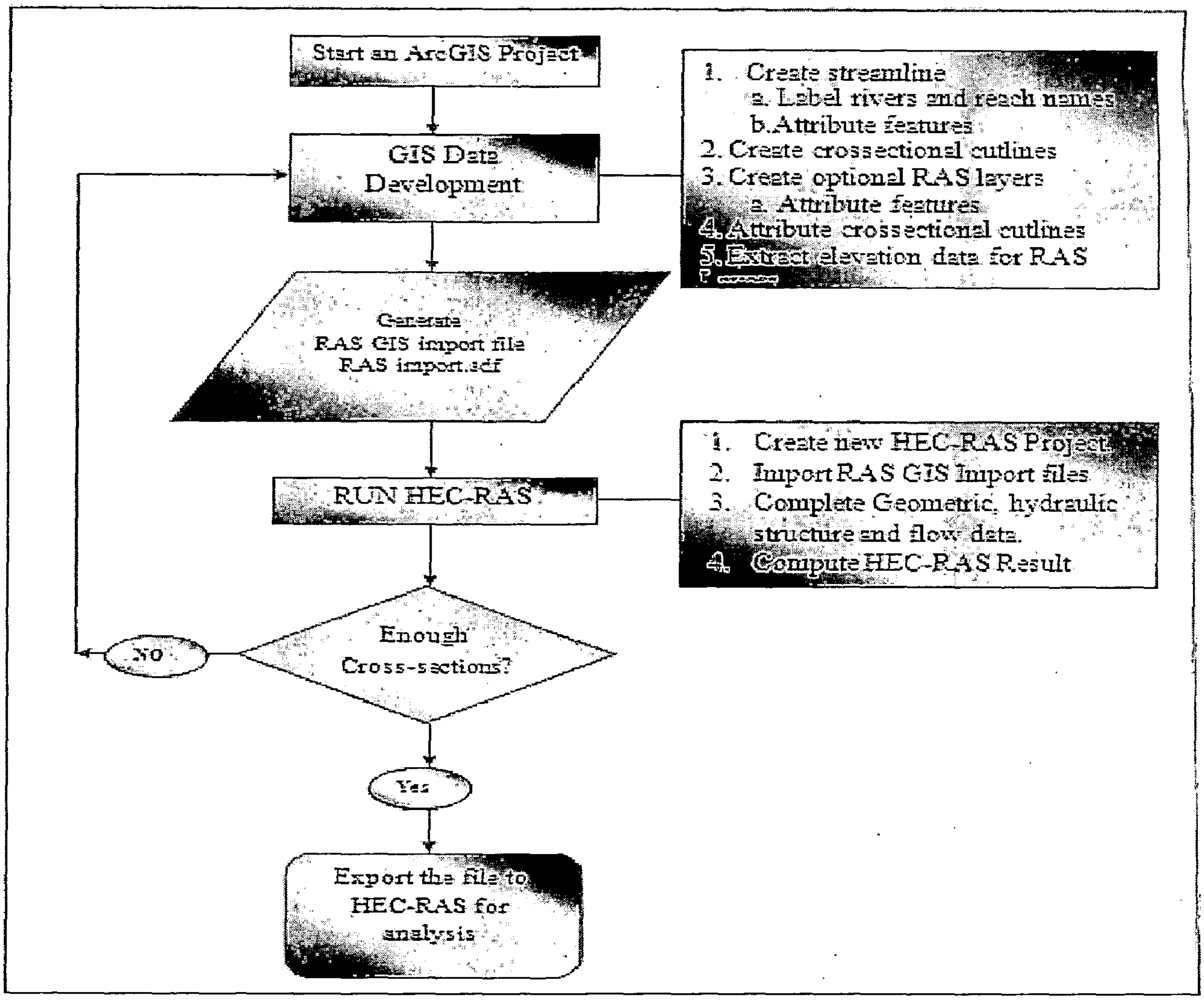


Fig 4.4: Working of the HEC-GeoRAS

4.7 Hydrologic Engineering Centre – River Analysis System (HEC- RAS)

HEC-RAS is an integrated package of hydraulic analysis programs in which the user interacts with the system through the use of a Graphical User Interface (GUI). The system is capable of performing Steady Flow water surface profile calculations and will include Unsteady Flow, Sediment Transport, and several hydraulic design computations in the future. The results of the model can be applied in floodplain management and flood insurance studies.

The hydraulic model requires as input the resulted hydrographs from Hydrologic Modeling System program (HMS); its parameters are representative cross-sections for each sub-basin, including left and right bank locations, roughness coefficients (Manning's n), and contraction and expansion coefficients. Roughness coefficients, which represent a surface's resistance to flow and are integral parameters for calculating water depth, were estimated by combining land use data with tables of Manning's n values such as that found in HEC-RAS. As present engineering studies are completed throughout the basin, more detailed cross-sectional data will be incorporated into the model.

For several years, the Hydrologic Engineering Centre (HEC) has distributed the HEC-RAS hydraulic modeling package. HEC-RAS is designed to aid in the determination of water surface profiles associated, based on the inputs describing the channel shape, hydraulic parameters, and flow. However, a consistent deficiency of hydraulic models such as HEC-RAS unable to connect the information concerning the water profiles with their physical locations on the land surface. Often the computed water surface elevations must be manually plotted in order to delineate floodplains.

4.7.1 Hydraulic Data (HEC-RAS)

The data files for a HEC-RAS project are categorized as follows: *plan data, Geometric data, steady flow data* or *unsteady flow data,* sediment data, and hydraulic design data. For the purposes of this research, only the first four data files were used.

4.7.1.1Plan Data

Usually the first step in performing a simulation is to put together a Plan. The Plan defines which geometry and flow data are to be used, as well as provide a description and short identifier for the run. If the geometry and flow data do not exist, then this action is performed after their creation. Also included in the plan information are the selected d flow regime and the simulation options. The user can select between en subcritical, supercritical, or mixed flow regime calculations.

4.7.1.2 Geometry Data.

Cross-section data represent the geometric boundary of the stream. Cross sections are located at relatively short intervals along the stream to characterize the flow carrying capacity of the stream and its adjacent floodplain. Cross-sections are required at representative locations throughout the stream and at locations where changes occur in discharge, slope, shape, roughness; at locations where levees begin and end; and at hydraulic structures (bridges, culverts, and weirs).

They required information for a cross section consists of: the river, reach and river station identifiers; a description; X & Y coordinates (station and elevation points); downstream reach lengths; Manning's roughness coefficients; main channel bank stations; and contraction and expansion coefficients. The cross-section information was gathered either from a physical survey or taken from topographic but in this case mostly cross-sections were extracted from HEC-GeoRAS due to the lack of survey on cross-sections (Figure 4.5).

4.7.1.3 Flow Data.

Once the geometric data is entered, the necessary flow data can be entered Steady Flow Data consist of: the number of profiles to be computed; the flow data; and the river system boundary conditions. At least one flow must be entered for every reach within the system. Additionally, flow can be changed at any location within the river system.

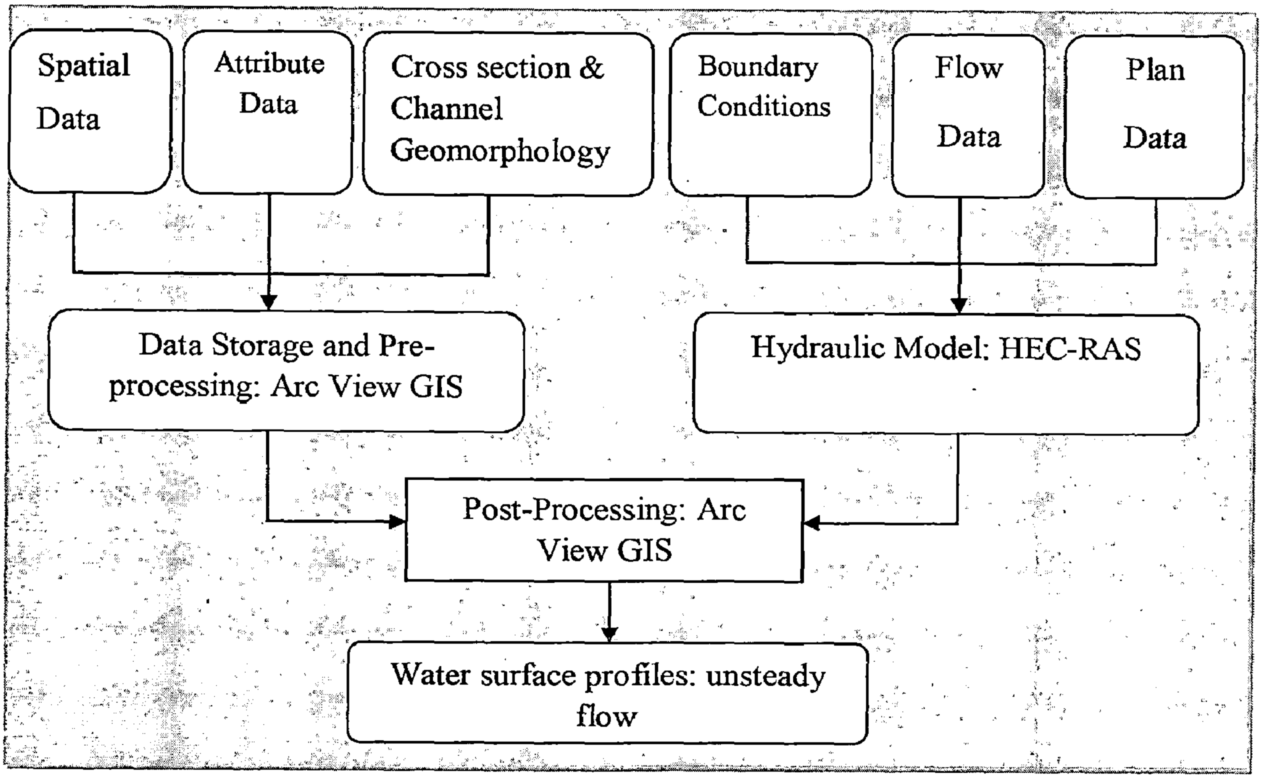


Fig 4.5: Modeling process of HEC-RAS.

Flow values must be entered for all profiles. Boundary conditions are necessary to establish the starting water surface at the ends of the river system (upstream and downstream). A starting water surface is necessary in order for the program to begin the calculations. In a subcritical flow regime, boundary conditions are only necessary at the downstream ends of the river system. If a supercritical flow regime is going to be calculated, boundary conditions are only necessary at the upstream ends of the river system. If a mixed flow regime calculation is going to be made, then boundary conditions must be entered at all ends of the river system.

The boundary conditions editor contains a table listing every reach. Each reach has an upstream and a downstream boundary condition. Connections to junctions are considered as internal boundary conditions. Internal boundary conditions are automatically listed in the table, base d on how the river system was defined in the geometric data editor. The user is only required to enter the necessary external boundary conditions (HEC-RAS Online Help, v 2.2)

4.6.2 Unsteady flow analysis

Rapid changes in flow and stage: If the inflow or the stage at a boundary is changing rapidly, the acceleration terms in the momentum equation (equation 4-16) become important. The leading example is dam break analysis; rapid gate openings and closures are another example. Regardless of bed slope, unsteady flow analysis should be used for all rapidly changing hydrographs.

Any information on events of record, high water marks, eyewitness accounts, etc can be useful in identifying such conditions. Eyewitness accounts of the Johnstown dam-break flood, for example, describe seiching in a major tributary valley. Occupants of floating houses made the trip up and down the valley several times as the currents flow reversed direction. Only an unsteady flow model with all acceleration terms intact is capable of modeling such an effect on downstream hydrographs and water levels.

a) Boundary Conditions

"Boundary conditions" is a mathematical term which specifies the loading for a particular solution to a set of partial differential equations. In more practical terms, boundary conditions for an unsteady flow model are the combination of flow and stage time series, which when applied to the exterior of the model either duplicates an observed event or generates a hypothetical event such as a design flood, or dam break. For an observed event, the accuracy of the boundary conditions affects the quality of the reproduction.

I).Upstream boundary conditions: The upstream boundary condition defines an input to be routed through the system. In most cases this is either a flow or stage hydrograph.

1).*Flow hydrograph.* A flow hydrograph is the classic upstream boundary condition where the time varying discharge is routed downstream and the corresponding stages are computed by the model at the upstream boundary and elsewhere.

2).*Stage hydrograph.* If a stage hydrograph is used as an upstream boundary, the corresponding flow is computed from the conveyance given by the geometric data. Because errors in stage data are less than errors in flow data, the stage hydrograph may have substantial advantages in accuracy over the flow hydrograph.

II).Downstream boundary condition. For subcritical flow, the downstream boundary condition introduces the effect of backwater into the model. Four types of downstream boundary conditions are stage hydrograph, flow hydrograph, rating curve, and Manning's equation.

1) Stage hydrograph. The classic downstream boundary is the stage hydrograph. The corresponding flow is calculated by the model. Because the stage hydrograph is observed, and therefore presumed accurate, the downstream end of a study reach can be located at a gauge.

2) *Flow hydrograph.* The flow hydrograph is a special purpose downstream boundary condition which is generally used to simulate a reservoir outflow or a pumping station if accurate outflow is known. For the flow hydrograph, the model calculates the corresponding stages.

3) *Rating curve.* A single valued rating curve describes a monotonic relationship between stage and flow. The rating curve is accurate and useful for describing a boundary condition at a free over fall, such as a spillway or at a falls, or at a pump station whose performance is defined by a schedule.

(4) *Manning's equation.* Manning's equation can be used as a downstream boundary condition for a free flowing stream when no other boundary condition is available. The model computes both stage and flow with the stage being a function of the friction slope.

4.7.3 Unsteady Flow Model

Unsteady flow equations. Derivations of the unsteady flow equations are presented in numerous references. Chow (1959), Fread (1978), and User's Manual for UNET (U.S. Army Corps of Engineers 1991b)] are three of such references. They can be obtained from the two-dimensional equations presented in Chapter 4 by assuming that the dependent variables only change in one direction, x, and that direction is along the river axis rather than being a Cartesian coordinate. Common formulations of the equations are as follows:

Continuity equation

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}+\frac{\partial s}{\partial t}=q_L \qquad (4.15)$$

Equation of momentum

$$\frac{\partial Q}{\partial t}+\frac{\partial (QV)}{\partial x}+gA\left[\frac{\partial Z}{\partial x}+s_f\right]=q_L V_L \qquad (4.16)$$

Q=flow

A=active flow area

S=storage area.

q_L=Lateral inflow per unit flow distance

V=Q/A=average flow gravity

g= acceleration of gravity

Z=water surface elevation

S_f=friction slope

V_L=average velocity of the lateral inflow

x= flow distance

t=time

The assumptions implicit to the unsteady flow equations are essentially the same as those for the steady flow equations: (a) the flow is gradually varied; that is, there are no abrupt changes in flow magnitude or direction; (b) the pressure distribution is hydrostatic; therefore, the vertical component of velocity can be neglected. This means, for example, that the unsteady flow equations should not be used to analyze flow over a spillway, and (c) the momentum correction factor is assumed to be 1.

The magnitude of each of the terms in the momentum equation plays a significant role in the hydraulics of the system. The terms in equation (4.16) are;

$\frac{\partial Q}{\partial x}$= local acceleration,

$\frac{\partial (Qv)}{\partial x}$ =Advective acceleration.

$\frac{\partial z}{\partial x}$= water surface slope

S_f=friction slope.

The water slope can be expressed as

$$\frac{\partial Z}{\partial x}=\frac{\partial h}{\partial x}-So \qquad (4.17)$$

In which h is the depth and

$\frac{\partial h}{\partial x}$= pressure term. S_o= bed slope.

CHAPTER 5

ANALYSIS AND RESULT

5.1 GENERAL

The analysis and discussions in this study are divided into three steps: (1) *Assessment of climate with statistical analysis*, to find out trend analysis with historic data like temperature and rainfall. (2) By using the Geographic Information System (GIS) tool, inventories of Glaciers and Glacial Lakes and *to study the Glacier Lake areal expansion for different Lakes for different years*: (3) Watershed delineation by using Archydro tool and *land use cover mapping using* ERDAS imagine so as to study the changes of the land cover in due course of time. And also to model the unsteady water surface profile of the River (Pochu) which has originated from the glacial lakes.

5.1.1 Trend Detection for Temperature and Rainfall

Daily temperature and rainfall data records are taken from one station for 15 years and converted into monthly for the statistical analysis of time series by using Mann Kendall (MK) test. For the statistical analysis for temperature and rainfall are given in the Table 5.1. It can be seen that the annual mean temperature ranges from 5 to 24.15°C, with an average of 15.34°C. The annual rainfall ranges from 412.3 to 839.4 mm, with an average of approximately 604.231 mm for the period of 14 years from 1996 to 2009.

Table 5.1: Statistical of annual mean temperature and annual rainfall of Bhutan.

Statistical	Temperature(°C)	Rain fall(mm)
Average	15.34	604.231
Standard Deviation	1.18	141.972
Coeff. Skewness	-0.32	0.435
Maximum Valuae	24.15	839.400
Minmum values	5	412.300
Range	19.15	427.100

The graphical trend analysis have been carried out for the annual average temperature maximum and minimum of January as shown in Figure 5.1. It is being observed that trend for maximum is upward and trend for minimum is in downward direction.

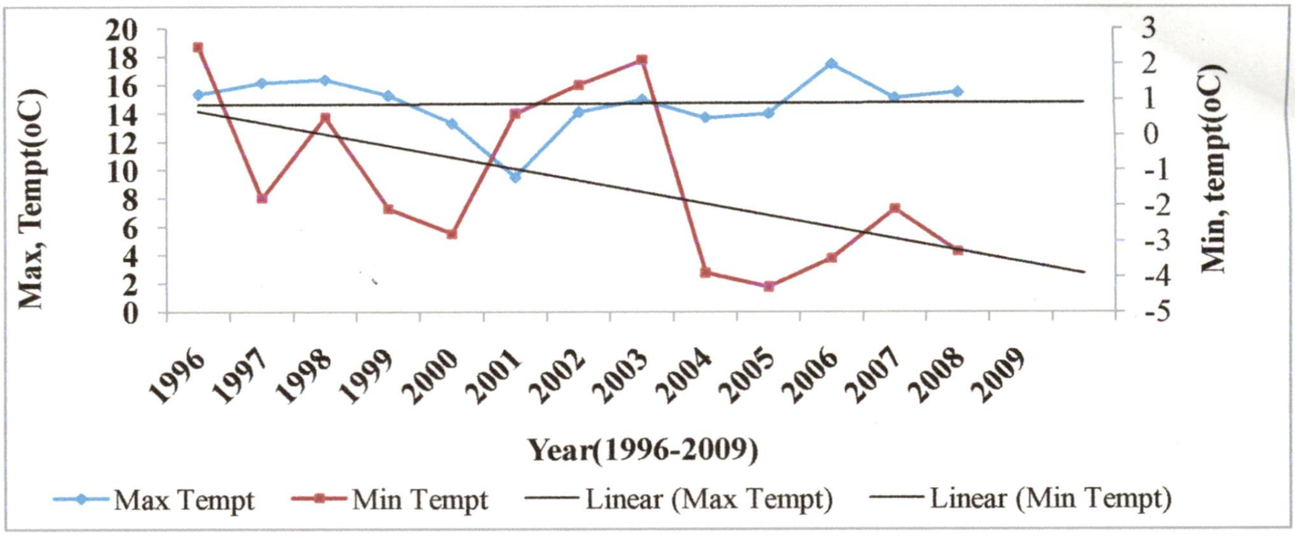


Fig 5.1: Trend analysis for January.

The above graphical observation conveys that dry season becomes drier and hot season become hotter. The Figure 5.2 shows the graphical trend analysis for the annual rainfall and annual mean temperature (Figure 5.3) and in case of temperature it shows increasing trend/upward trend but in case of annual rainfall, it shows the decreasing trend/downward trend.

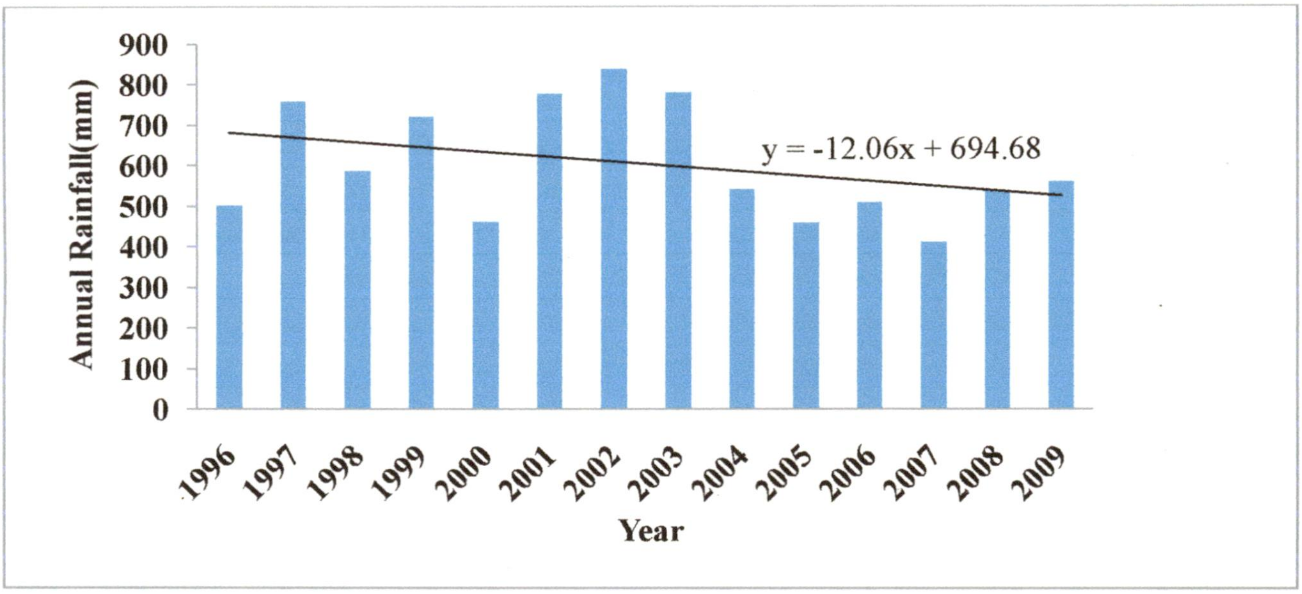


Fig 5.2: Annual rainfall (1996-2009)

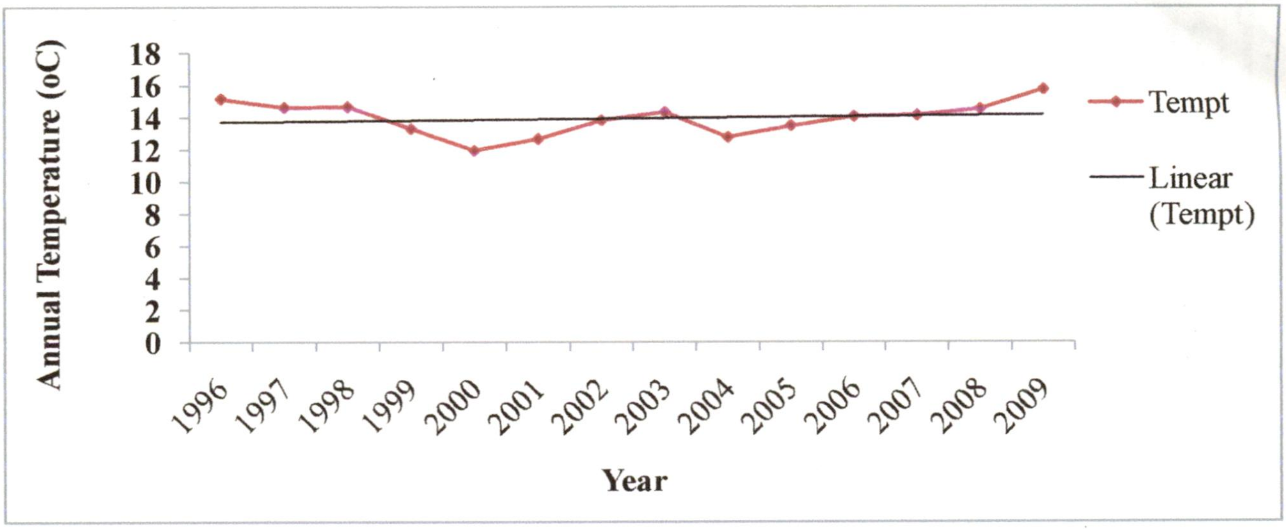


Fig 5.3: Trend analyses for Annual mean Temperature

The Figure 5.4 shows the two years moving averages of annual rainfall and the annual mean temperature from 1996 to 2009. The sudden change of point that is also called as inflection point was 2001 in both cases of rainfall and temperature. It is seen in figure below.

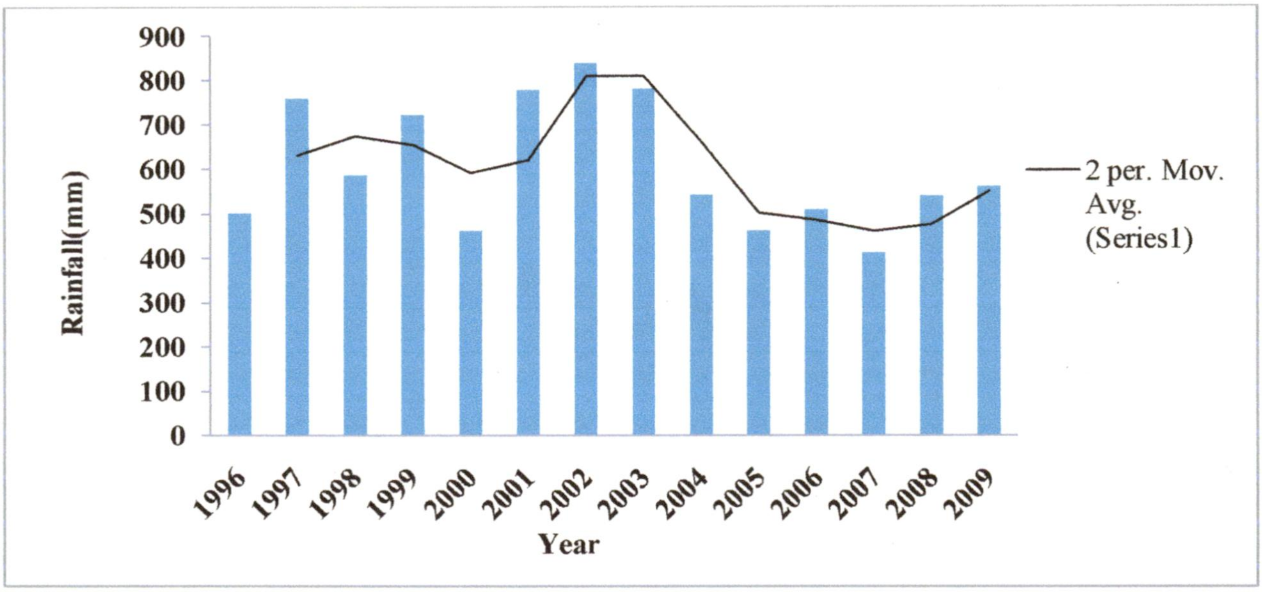


Fig 5.4: Moving averages for rainfall

Moving averages of temperature are shown in Figure 5.5 which, it can be found that the temperature starts increasing from 2001 onwards which means there is sudden change (inflection point).

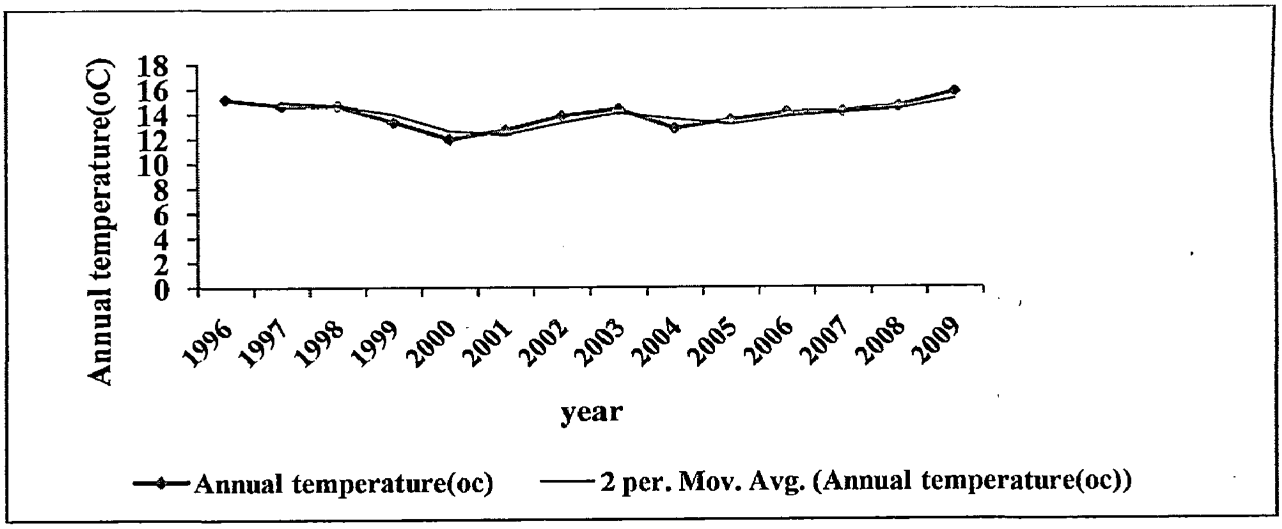


Fig 5.5: Moving averages of temperature

5.2 MANN-KENDALL ANALYSIS.

The Mann-Kendall test was performed to evaluate the trend of precipitations at rain gauge station. Using statistical methods, the determination of temporal trends and their spatial distribution of historical annual and seasonal precipitation and temperature series in Bhutan is necessary. The Mann-Kendall test is a non-parametric test for identifying trends in time series data.

5.2.1Temperature trend analysis

The mean annual temperature is about 21 to 22°C and trend analysis is done from the period 1996-2009 by using the Mann Kendall test.The values of Mann Kendall statistic Z_{mk} and Sen's slope (Q) were used for different records. The negative value and positive value of Zmk shows the decreasing trend and increasing trend respectively.

There are four season in Bhutan and it has been analyzed as given in the Table 5.1 by the statistics method. The values of Mann-Kendall statistic Zmk and Sen's slope (Q) in long term period of different months are given in Table 5.2. According to the Sen;s slope, we can apparently observed that in the season winter and summer, it gives the bigger values 0.065°C and 0.073°C respectively. The autumn season gives the smallest values of 0.011°C. So the annual increment for the 15 years is 0.64°C and yearly increment is 0.043°C per year till now.

Table 5.2: Trend of seasonal temperature (°C) of Bhutan

Year (1995-09)	Winter (Dec-Feb)	Spring (March-May)	Summer (June-Aug)	Autumn (Sept-Nov)	Annual
Zmk	0.6	0.22	0	0.11	0.04
Q	0.065	0.035	0.012	0.011	0.043

As it is shown clearly by the graphical below that the mean temperature of Sen's estimate slope is showing increasing trend.The trend rates of the winter mean temperature have revealed an increasing trend, which is significant with 0.065°C per year (0.97°C for 15 years. For spring, mean temperature revealed a weak and insignificant increasing trend with 0.035 °C per year (0.52 °C for 15 years) For summer and autumn increasing trend is very weak and insignificant with 0.012°C and 0.011°C respectively (for summer, 0.18°C and for autumn 0.16°C for 15 years). Among the seasons, the most increasing trend is highest in winter as it is shown in Figure 5.6 whereas annual mean temperature is presented in Figure 5.7.

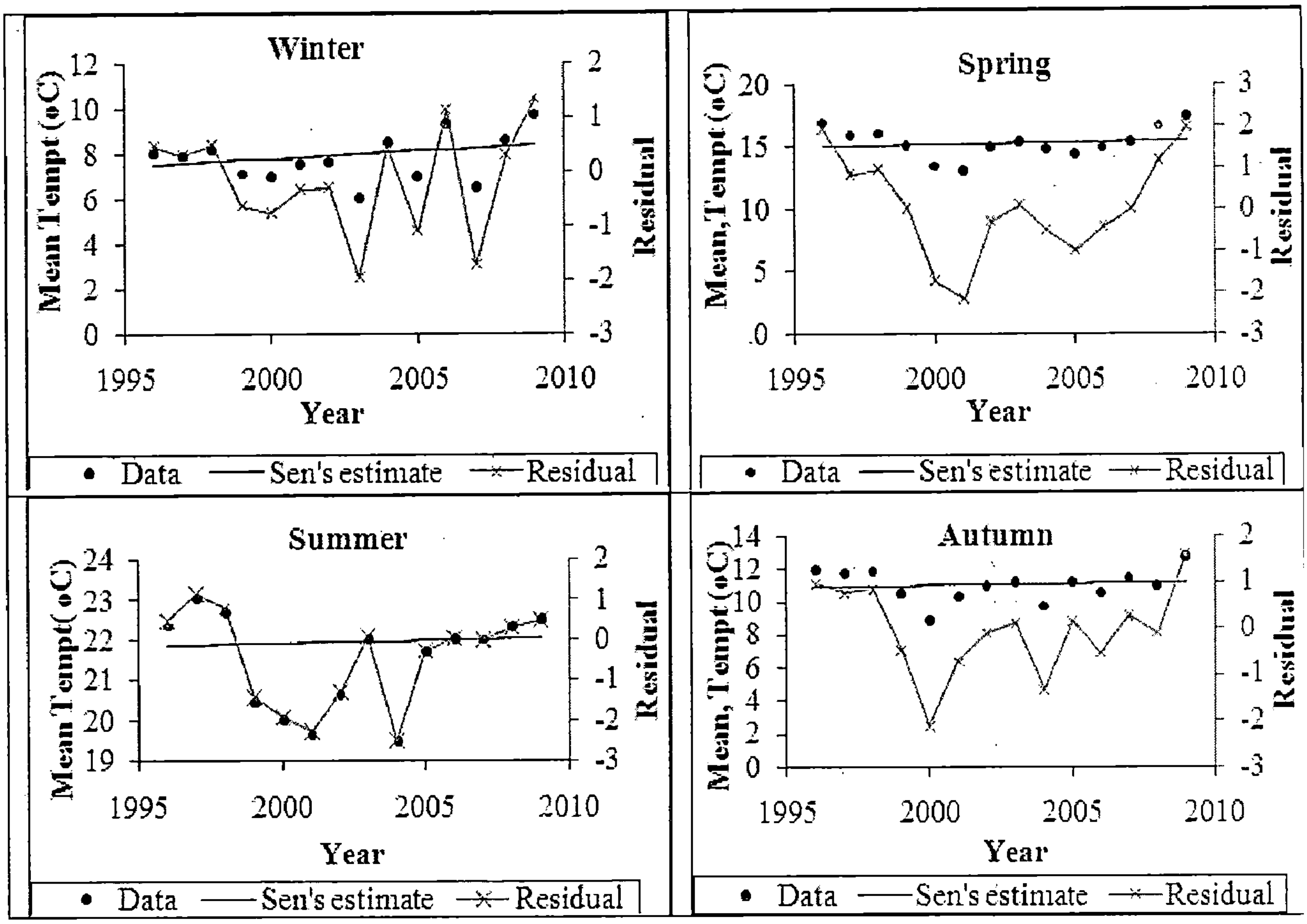


Fig 5.6: Mean temperature of four seasons

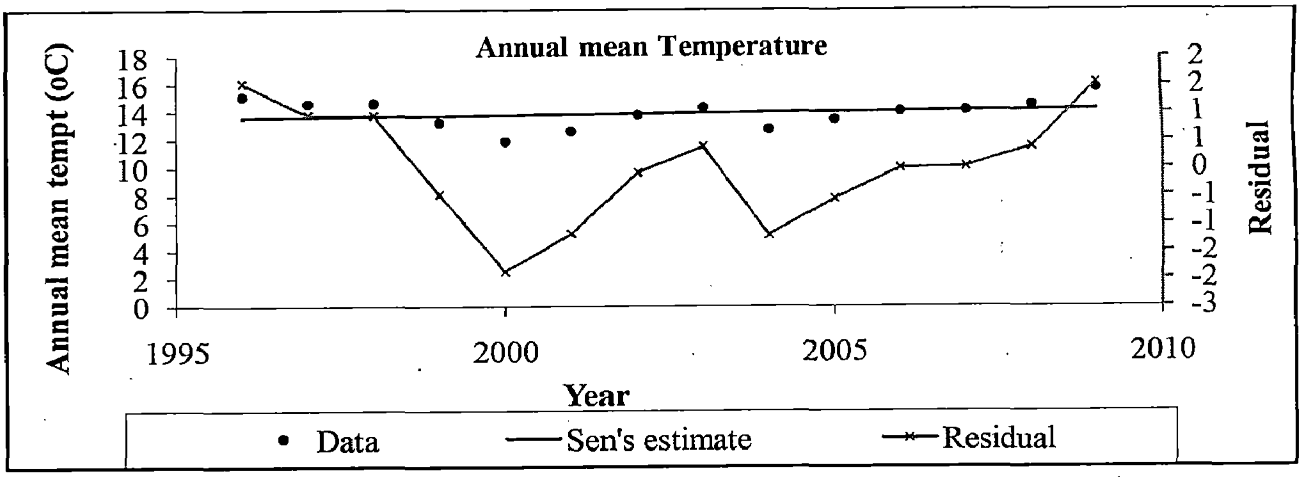


Fig 5.7: Annual mean temperature (°C)

Now by analyzing the monthly temperature for 15 years, it has been shown that the biggest values/slopes are given by January and December which is 0.14°C in both the months. So in the month of August there is no trend and the lowest slope/values is in the months of September and October is 0.01°C in both of September and October (Table 5.3).

Table 5.3: Trend of monthly temperature (°C) of Bhutan

Year (1995-2009)	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Zmk	0.55	0.33	0.49	0.44	0.22	0.38	0.55	0.00	0.22	0.16	0.11	0.88
Q	0.14	0.08	0.07	0.08	0.03	0.03	0.11	0.00	0.01	0.01	0.02	0.14

5.2.2 Rainfall trend analysis

As it is already mentioned that there are four seasons in Bhutan and the trend of each rainfall season is statistically analyzed by using the Mann-Kendall Method, the results of those trends are being tabulated along with the median of Sen's slope. The mean rainfall (mm) is varying from 600-605 mm and historical record of data is from 1996 to 2009. According to the Mann-Kendall test result, the highest slope is in the Autumn season and lowest one is in the summer season with negative value of -17.9 mm and is the only season with decreasing trend. The other seasons are showing increasing trend with highest value of 3.83mm and the lowest one with 0.1 mm and the annual rainfall is showing decreasing trend since 1996 to till date (Figure 5.4 & Table 5.8).

Year (1995-09)	Winter (Dec-Feb)	Spring (March-May)	Summer (June-Aug)	Autumn (Sept-Nov)	Annual
Z_{mk}	0.16	0	-1.97	0.55	-0.66
Q	0.1	0.26	-17.90	3.83	-9.71

Table 5.4: Rainfall trend analysis of four seasons

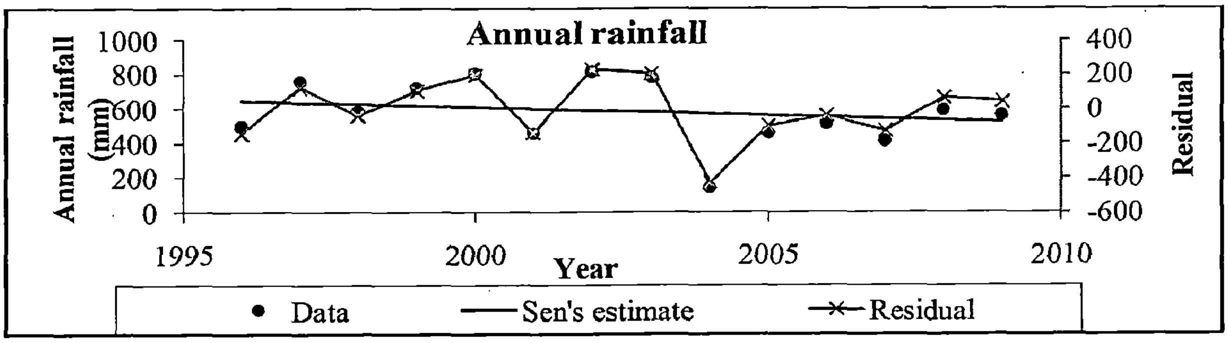


Fig 5.8: Rainfall trend analysis annually

The trend analysis of rainfall in different seasons is shown in Figure 5.9 four seasons and it is revealed that the increasing trend is very weak and insignificant for most of the seasons. And then it is very clearly indicated that summer season is the decreasing trend and the autumn is showing increasing trend with 3.83 mm per year (57.45 mm for 15 years) and the annual decreasing trend is -9.71mm (decreased 145.65 mm for 15 year) (Figure 5.9)

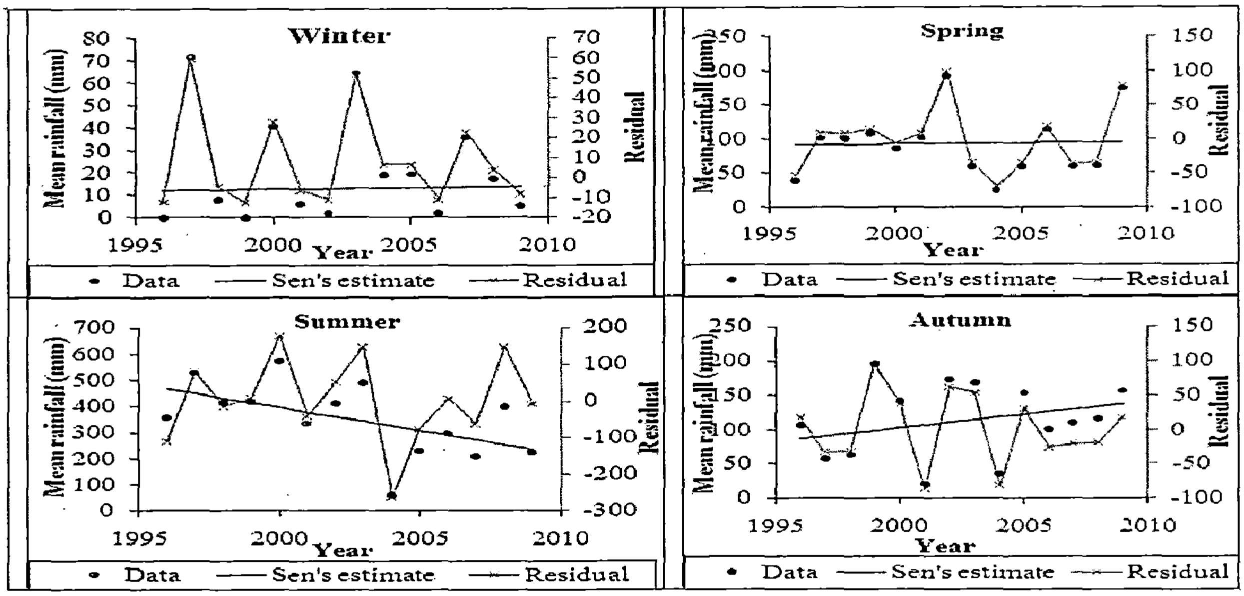


Fig 5.9: Mean rainfall for four seasons

The Table 5.5 is showing the monthly analysis of rainfall for 15 years. From the following analysis only few months are showing increasing trend and most of them are showing decreasing trend significantly and negative slope of the year are found in June and July with -5.65 and -6.00 mm respectively. The more significant trend of increasing is the months of April, May and October with the values of 0.1, 1.22 and 1.9mm respectively.

Year (1995-2009)	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Zmk	1.12	0.00	-0.94	0.05	0.44	-1.64	-1.31	-1.20	-0.22	1.42	0.53	0.53
Q	0.00	0.00	-1.60	0.10	1.22	-5.65	-6.00	-3.69	-0.77	1.90	0.00	0.00

Table 5.5: Variation of monthly rainfall of Bhutan

5.3 STUDY OF GLACIERS.

5.3.1 Decreasing rate of Glaciers thickness.

According to the historical data, the thickness can be found with the following formula. To estimate the ice reserves, it is an utmost necessity to have the mean thickness of the glaciers. Since the mean glacier thickness data are not available, it has been estimated using the equation developed for the **Tianshan** Mountains (Chaohai Liu and Liangfu Ding,1986) and applied in Nepal (Mool et al., 2001). It is necessary to have the area of the glaciers to estimate the thickness. The very concept of development of this formula was purely based on the Glacier as the area of ice increases the thickness of ice increases too.

$$H = -11.32 + 53.21F^{0.3} \quad 5.1$$

Where, H = mean ice thickness in meter and F = area of glacier in square kilometer. The ice reserves were estimated by multiplying the mean thickness with the area of the glacier. The following represents the area and thickness of Glacier/snow coverage for each glacial lake. The name assigned for the glaciers, B-GL for Bechung glacial lake, R-GL for Rapstreng glacial lake, T-GL for glacial lake and L-GL for Luggye glacial lake. The Table 5.6 shows the area of each glacier located to each glacial lake and variation of thickness with changing of glacier area (Figure 5.10).

Table: 5.6 Area and thickness of glaciers for different years.

	1990		2001		2007		2009	
Names of glaciers	Glacier area (m)	Glaciers thickness (m)	Glacier area (m)	Glaciers Thickness (m)	Glacier area (m)	Glaciers thicknes -s(m)	Glacier area (m)	Glaciers thicknes -s (m)
Bechung (B-GL)	4843388	74.08	4326388	71.27	2163739	55.72	2026739	54.48
Rapstreng (R-GL)	3071857	63.18	2873857	61.69	1438311	48.04	1228311	45.30
Thorthormi (T-GL)	5431016	77.08	5255016	76.24	2629150	59.80	2569150	59.31
Luggye (L-GL)	5527259	77.56	5252259	76.19	2624224	59.72	2584224	59.39

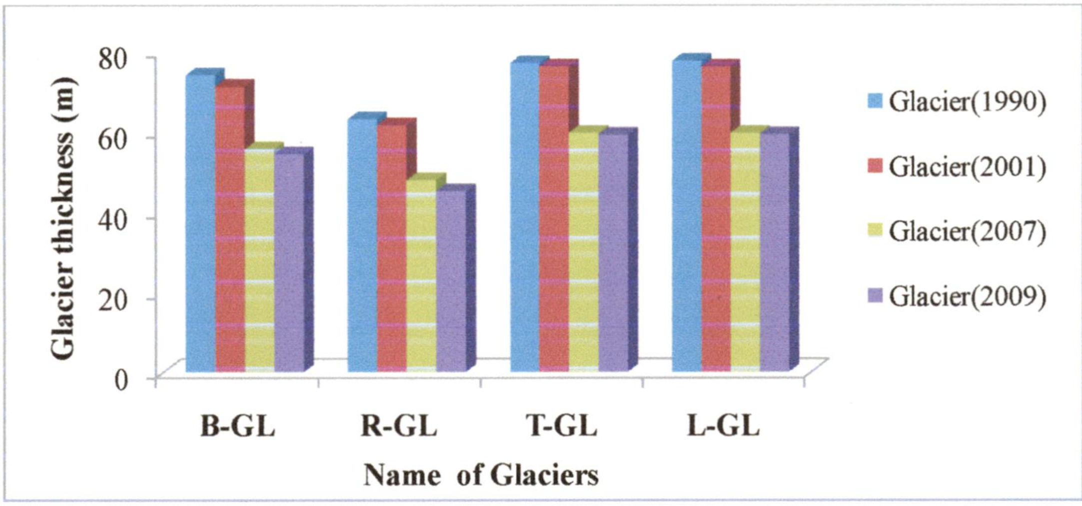


Fig 5.10: Variation of thickness of glaciers for different year.

As the temperature keep on increasing, the thickness of the ice also keep on decreasing as it is found out and the rate of thickness for those Glaciers from 1990 to 2001,2001 to 2007 and 2007 to 2009 are given in Table 5.7. It is seen that thickness of those Glaciers are obviously decreasing at the following rate. From the following observation, it is noticed that, the rate of decreasing is more from 2001 to 2007, 2007 to 2009 than in1990 to 2001 although the gaps between the years was more in earlier 1990s. The range of thickness per year from 2001 to 2007 was from 1.95m to 2.35m. The overall reduction of thickness from 1990 to 2009 was approximately almost same from 0.99 m to 1.09 m for every glacier.

Table 5.7: Variation of thickness of Glaciers of Lunana region

	1990 to 2001	2001 to 2007	2007 to 2009	1990 to 2009
Name of Glaciers	**Glaciers thickness (m/yr)**	**Glaciers Thickness (m/yr)**	**Glaciers Thickness (m/yr)**	**Glaciers Thickness (m/yr)**
Bechung (B-GL)	0.26	2.22	0.62	1.09
Rapstreng (R-GL)	0.14	1.95	1.37	0.99
Thorthormi (T-GL)	0.08	2.35	0.25	0.99
Lugye (L-GL)	0.12	2.35	0.16	1.01

5.3.2 Retreating Rate of Glaciers

There are respective Glaciers contributing the water to its respective Lakes. Retreating rate is the shifting of toes of the Glaciers and with increase in temperature, it is seen and found out that those Glaciers are retreating at different rate as it is represented in the following manners. In the similar manners, it has been noticed that the biggest retreating rate is the Bechung Glacier around 12.52 meter per year from 1990 to 2001 and 64.2 meter per year from 2001 to 2007 from Thorthormi Glacier. For the overall the retreating rate for 18 year from 1990 to 2007, it is found that the biggest retreating rate was Thorthormi Glaciers around 35.27 meters per year and smallest is around 15.26 meter per year for Bechung Glaciers. So, one strange thing that has been noticed is, rate of retreating was more from the year 2001 to 2007 for every glacier than the year 1990 to 2001(Table 5.8)

Table 5.8: Retreating rate meter per year for different of year and for 18 year

Glaciers	Retreating rate (m/year)1990 - 2001	Retreating rate (m/yr) 2001 to 2009	Year 2007-2009	Glaciers	1990 - 2007 (m/year)
Bechung	12.52	18	Some patches of glaciers are disappeared in upper part but no significance of retreating from the lower portion	Bechung	15.26
Rapstreng	12.35	51.94		Rapstreng	32.15
Thorthormi	6.34	64.2		Thorthormi	35.27
Luggye	not identified	46.99		Luggye	23.49

5.3.3 Retreating of Glacier in terms of area.

From the Table 5.9, it is noticeable that glacier of Thorthormi was retreated over larger area and Luggye glacier was the second to be retreated 0.376 km^2 per year and 0.375 km^2 per year respectively. The lowest one is the Rapstreng glaciers with the value of 0.205 km^2 per year. When coming to the year 2007 to 2009, there were not much significant changes but some patches were disappeared at the upper region of its respective glaciers.

Table: 5.9 Retreated areas within each span of year in km^2 per year

Glaciers\Year	1990-2001	2001-2007	2007 to 2009		1990-2007
	Km^2/yr	km^2/yr	Km^2/yr	Glaciers\Year	Km^2/yr
Bechung	0.047	0.309	Not significance but some patches are shrank at upper region	Bechung	0.178
Rapstreng	0.018	0.205		Rapstreng	0.112
Thorthormi	0.016	0.376		Thorthormi	0.196
Luggye	0.025	0.375		Luggye	0.200

The following Table 5.10 indicates the total for 1990, 2001, 2007 and 2009 and also the areas that have been shrank between those years. In the year 2009, no change was and some variation or insignificance of changes. The percentage (%) changes of glaciers area were greater from 2001 to 2007 than in 1990 to 2001 as it is indicated (Table 5.11)

Table 5.10: Total area and its changes (1990-2001)

Name of Glaciers	1990 Total Area (km^2)	Area shrank in km^2 from 1990 to 2001	2001 Area km^2	Area shrank in km^2 from 2001 to 2007	2007 Area km^2	Patches of area lost in km^2 from 2007to 2009	2009 Area km^2
Bechung	4.84	0.52	4.33	2.1	2.16	0.137	2.03
Rapstreng	3.07	0.2	2.87	1.43	1.44	0.21	1.23
Thorthormi	5.43	0.18	5.26	2.59	2.63	0.06	2.57
Luggye	5.53	0.28	5.25	2.59	2.62	0.04	2.58

Table 5.11: % of area changes for different years.

Names of Glaciers	Year	Total area (km^2)	Change of Glaciers area(km^2)	Change of Glaciers area (%)
Bechung (B-GL)	1990	4.84		
	2001	4.33	0.52	11
	2007	2.16	2.1	48
	2009	2.03	0.137	6
Rapstreng (R-GL)	1990	3.07		
	2001	2.87	0.2	7
	2007	1.44	1.43	50
	2009	1.23	0.21	15
Thorthormi (T-GL)	1990	5.43		
	2001	5.26	0.18	3
	2007	2.63	2.59	49
	2009	2.57	0.06	2
Luggye (L-GL)	1990	5.53		
	2001	5.25	0.28	5
	2007	2.62	2.59	49
	2009	2.58	0.04	2

The Figures 5.11 indicates the area retreated/shrank during the year from 1990 to 2007 and the changes here are, noticeable with brown color showing the retreating area. The Figure 5.11 is the area of retreated glaciers from 1990 to 2007, B-GL is glaciers for Bechung Lake, R-GL is glaciers for Rapstreng Lake, T-GL is glaciers for Thorthormi Lake and L-GL is glaciers for Luggye Lake. And also R1 is glacier retreated for Bechung, R2 is glacier retreated for Rapstreng, R3 is glacier retreated for Thorthormi and R4 is for glacier retreated for Luggye as in Figure 5.11.

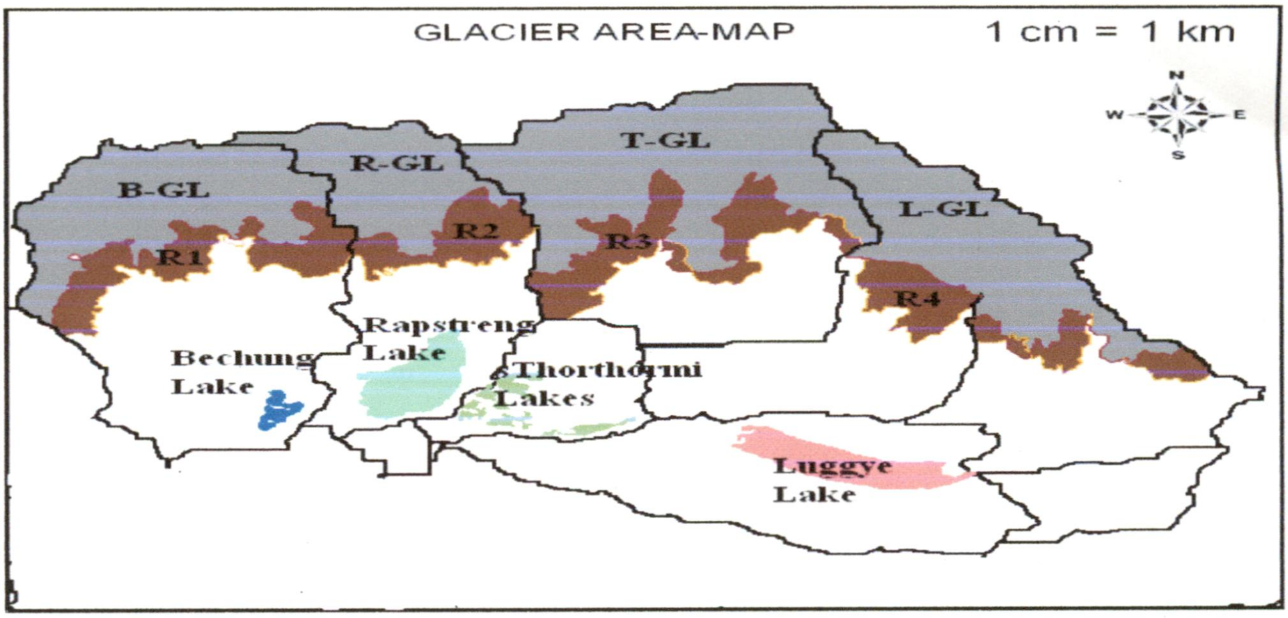


Fig 5.11: Area of glaciers and its retreated area (1990-2007)

The Figure 5.12 indicates changes between 1990 to 2009, for almost 21 years of duration and the changes between 2007 and 2009 were not that significant but some of upper part of the Glaciers were melted leaving the barren rocks/land. The shifting area from 2007 to 2009 was quite insignificant and it is very difficult to find its retreating rate.

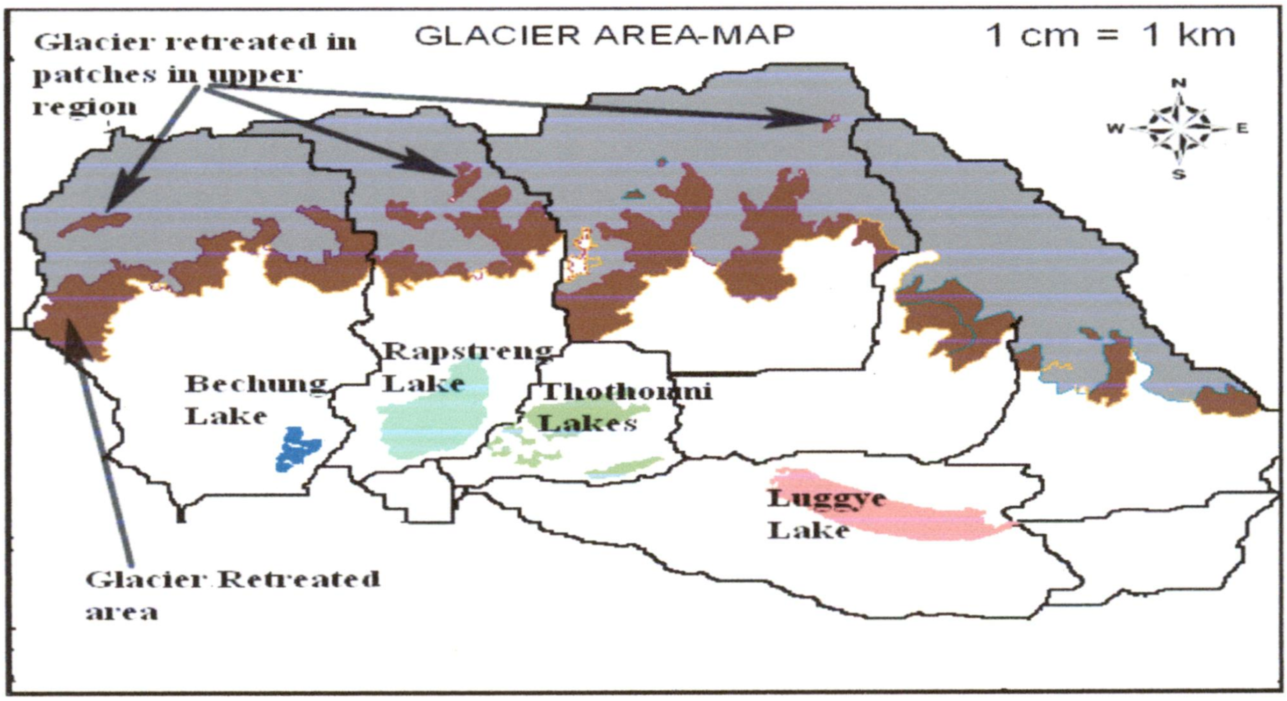


Fig 5.12: Area of retreated/shrank (1990-2009)

5.4 STUDY OF GLACIAL LAKES

5.4.1 Expansion rate of Glacial Lakes in term of area and perimeter

By using the land satellite maps of four different years of 1990, 2001, 2007 and 2009 with the help of ArcGIS 9.3 tools, the following are the result of area differences within those spans of year are given in Table 5.12. The area of each Glacial Lake is found out by digitizing Glacial Lakes. It is being noticed that Glacial Lakes are keep on increasing its size year after year. The Table 5.12 shows the areal expansion within those particular years. In similar way, the perimeter is also shown and it has been noticed that it keeps on increasing yearly in all the Glacial Lakes. In the year 1990, there was no existence of Bechung Glacial Lakes but in the year 2001, Bechung Glacial Lake was appeared to be existed with the area of 0.06 km^2 and again in the year 2007 there was another Glacial lake formation in the Bechung vicinity. But in the year 2009, these two Bechung Lakes were merged into one Glacial Lake. It has been noticed that most of the Glacial Lakes were increasing at almost uniformly but the Thorthormi_1 Glacial Lake was found to be increasing abruptly in its size from 1990 to 2001 and 2007 but in 2009 it has been reduced due to mitigation measures conducted by Royal government of Bhutan. Therefore, it is noticing that most of sub Glacial Lakes of Thormthormi were tends to reduce their sizes in late 2009.

Table 5.12: Variations of areas and perimeters of different years

		Location		Area		Perimeter	
Year	Names of Lakes	Latitude & Longitude	Elevati-on(m)	m^2	Km^2	m	Km
1990	Rapstreng	28'06'24.01"N 90'14'51.76"E	4368	1135073.4	1.14	4750.1	4.8
	Thorthormi_1	28'06'21.78"N 90'15'48.95"E	4454	37097.5	0.04	1404.7	1.4
	Thorthormi_2	28'06'15.23N 90'15'21.95"E	4459	18700.5	0.02	872.8	0.9
	Thorthormi_3	28'06'06.66"N 90'15'25.61"E	4462	31396.8	0.03	1290.5	1.3
	Thorthormi_4	28'05'52.78"N 90'16'05.16"E	4461	111609.8	0.11	2155.8	2.2
	Luggye	28'06'02.13"N 90'15'18.08"E	4459	978421.2	0.98	4997.8	5.0
	Drukchung	28'05'12.34"N 90'19'34.14"E	4706	135733.0	0.14	2218.5	2.2
2001	Bechung_1	28'06'07.64"N 90'13'49..51"E	4337	64049.8	0.06	2402.4	2.4
	Rapstreng	28'06'24.01"N 90'14'51.76"E	4368	1173815.3	1.17	5124.8	5.1
	Thorthormi_1	28'06'21.78"N	4454	335744.8	0.34	2880.5	2.9

		90'15'48.95"E					
	Thorthormi_2	28'06'15.23N 90'15'21.95"E	4459	49708.6	0.05	1385.5	1.4
	Thorthormi_3	28'06'06.66"N 90'15'25.61"E	4462	38185.1	0.04	1338.6	1.3
	Thorthormi_4	28'05'52.78"N 90'16'05.16"E	4461	136944.8	0.14	2199.1	2.2
	Thorthormi_5	28'0602.13"N 90'15'18.08"E	4459	47466.4	0.05	1560.9	1.6
	Luggye	28'06'02.13"N 90'15'18.08"E	4459	1158984.8	1.16	5599.0	5.6
	Drukchung	28'05'12.34"N 90'19'34.14"E	4706	121970.5	0.12	2299.6	2.3
2007	Bechung_1	28'06'07.64"N 90'13'49..51"E	4337	111317.6	0.11	2420.6	2.4
	Bechung_2	28'06'00.17"N 90'13'48.25"E	4336	39754.7	0.04	1421.8	1.4
	Rapstreng	28'06'24.01"N 90'14'51.76"E	4368	1225310.5	1.23	5415.0	5.4
	Thorthormi_1	28'06'21.78"N 90'15'48.95"E	4454	651363.3	0.65	5183.8	5.2
	Thorthormi_2	28'06'15.23N 90'15'21.95"E	4459	57802.6	0.06	1601.6	1.6
	Thorthormi_3	28'06'06.66"N 90'15'25.61"E	4462	79103.2	0.08	2026.3	2.0
	Thorthormi_4	28'0602.13"N 90'15'18.08"E	4459	144131.1	0.14	2233.4	2.2
	Thorthormi_5	28'05'52.78"N 90'16'05.16"E	4461	48020.9	0.05	1595.9	1.6
	Luggye	28'06'02.13"N 90'15'18.08"E	4459	1261337.2	1.26	6292.9	6.3
	Drukchung	28'05'12.34"N 90'19'34.14"E	4706	112251.0	0.11	2170.6	2.2
2009	Bechung_3	28'06'07.64"N 90'13'49..51"E	4337	172287.93	0.17	3378.40	3.38
	Rapstreng	28'06'24.01"N 90'14'51.76"E	4368	1254513.82	1.25	6060.49	6.06
	Thorthormi_1	28'06'21.78"N 90'15'48.95"E	4454	164989.98	0.16	2669.68	2.67
	Thorthormi_2	28'06'15.23N 90'15'21.95"E	4459	77709.97	0.08	1839.17	1.84
	Thorthormi_3	28'06'06.66"N 90'15'25.61"E	4462	96807.64	0.10	2397.41	2.40
	Thorthormi_4	28'05'52.78"N 90'16'05.16"E	4461	128055.54	0.13	2952.26	2.95
	Thorthormi_5	28'0602.13"N 90'15'18.08"E	4459	71805.98	0.07	2229.50	2.23
	Luggye	28'06'02.13"N 90'15'18.08"E	4459	1412751.08	1.41	8329.81	8.33
	Drukchung	28'05'12.34"N 90'19'34.14"E	4706	115490.57	0.12	2297.45	2.30

The positive and negative sign shows the increasing rate and decreasing rate respectively. And most of the Glacial Lakes are increasing at an alarming rate but it has been noticed that

Drukchung Glacial Lake is at the rate of decreasing presently and the Lakes of Thorthormi_1 and Thorthormi_4 are too decreasing but these are due to the mitigation measures taken in early 2009 (Table 5.13).

Table 5.13: Summary of variation of glacial lakes for different years

Year	Names of Lakes	Elevation(m)	Km^2	Difference of Area (Km^2)	% inc/dec of Area
1990	**Rapstreng**	4368	1.14		
2001	**Rapstreng**	4368	1.17	0.04	3.41
2007	**Rapstreng**	4368	1.23	0.05	4.39
2009	**Rapstreng**	4368	1.25	0.03	2.38
1990	**Thorthormi_1**	4454	0.04		
2001	**Thorthormi_1**	4454	0.34	0.30	805.03
2007	**Thorthormi_1**	4454	0.65	0.32	94.01
2009	**Thorthormi_1**	4454	0.16	-0.49	-74.67
1990	**Thorthormi_2**	4459	0.02		
2001	**Thorthormi_2**	4459	0.05	0.03	165.81
2007	**Thorthormi_2**	4459	0.06	0.01	16.28
2009	**Thorthormi_2**	4459	0.08	0.02	34.44
1990	**Thorthormi_3**	4462	0.03		
2001	**Thorthormi_3**	4462	0.04	0.01	21.62
2007	**Thorthormi_3**	4462	0.08	0.04	107.16
2009	**Thorthormi_3**	4462	0.10	0.02	22.38
1990	**Thorthormi_4**	4461	0.11		
2001	**Thorthormi_4**	4461	0.14	0.03	22.70
2007	**Thorthormi_4**	4459	0.14	0.01	5.25
2009	**Thorthormi_4**	4461	0.13	-0.02	-11.15
2001	**Thorthormi_5**	4459	0.05		
2007	**Thorthormi_5**	4461	0.05	0.00	5.34
2009	**Thorthormi_5**	4459	0.07	0.02	43.61
1990	**Luggye**	4459	0.98		
2001	**Luggye**	4459	1.16	0.18	18.45
2007	**Luggye**	4459	1.26	0.10	8.83
2009	**Luggye**	4459	1.41	0.15	12.00
1990	**Drukchung**	4706	0.14		
2001	**Drukchung**	4706	0.12	-0.01	-10.14
2007	**Drukchung**	4706	0.11	-0.01	-7.97
2009	**Drukchung**	4706	0.12	0.00	2.89
2001	**Bechung**	4337	0.06		
2007	**Bechung**	4337	0.11	0.05	73.80
2009	**Bechung**	4337	0.17	0.06	54.77

5.4.2 Rapstreng Lake

This is one of the potentially dangerous Glacial Lakes and the Figure 5.13 showing the increment of areal and perimeter respectively and it can be seen apparently that there is some increase of Glacial Lake within the certain span of years. The gaps of years between satellites maps are 11, 7 and 3 from 1990 to 2001, 2001 to 2007 and 2007 to 2009 respectively. Although there was short duration in recent years but still it is shown more rapid increase than that of 1990 to 2001. This Glacial Lake is below 60 to 70 m below the Thorthormi Lakes and if these two are merged together, there will be a great GLOF of outburst and debris flow at the downstream of the valley.

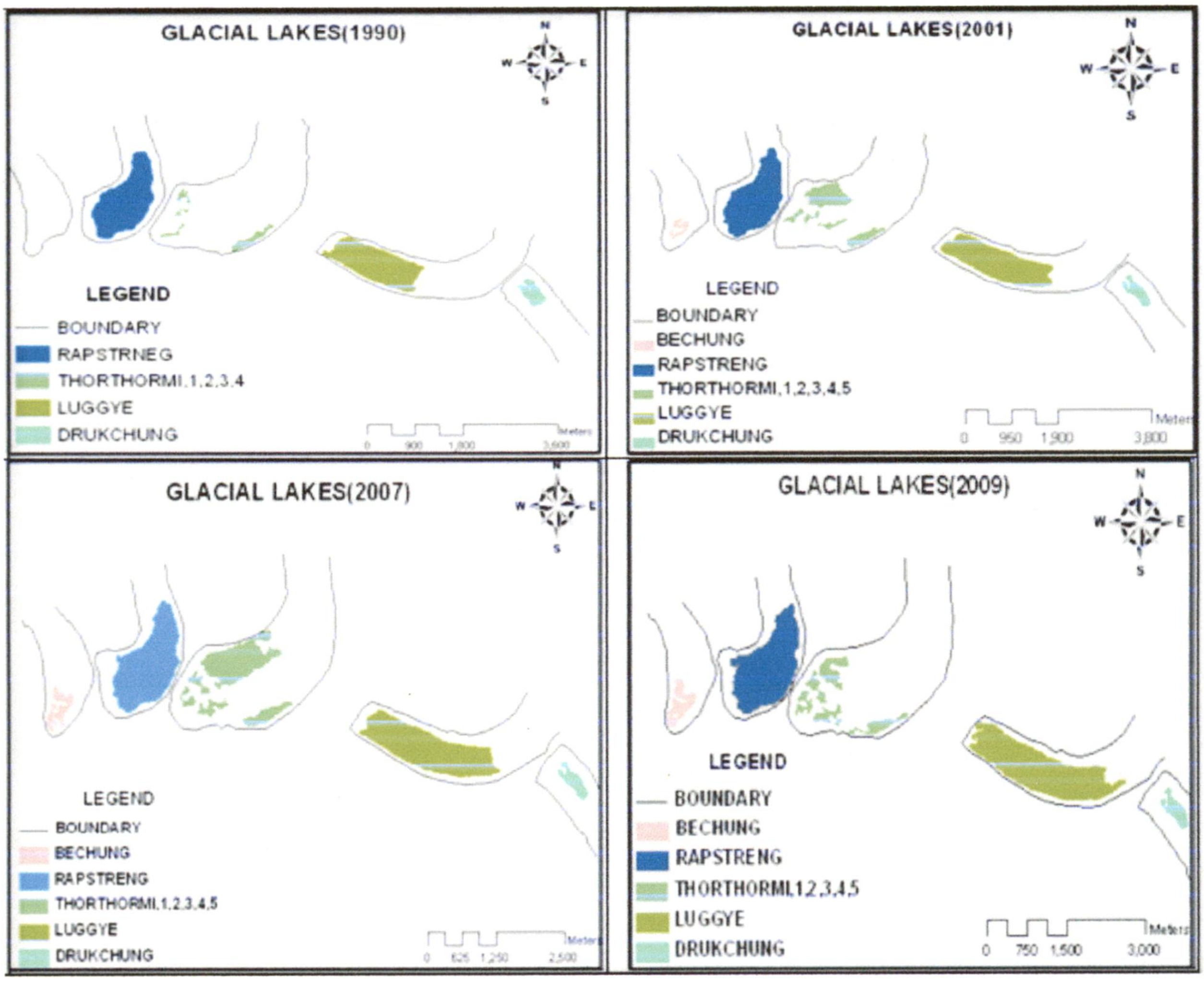


Fig 5.13: Glacial Lakes for different years

5.4.3 Thorthormi lakes

This is one of the fastest increasing Glacial Lakes among the Lakes and it has a number of lakes within the same vicinity. So it has been a main concern for the people of Bhutan and at present it is under mitigation measures started in early 2009 by draining out water through the artificial drainages. From 1990 to 2007, it keeps on increasing but in 2009 its sizes starts reducing. The Figure 5.13 shows the areal and perimeter expansion for different years but there are around five Thorthormi Lakes. The Thorthtormi_1 and thorthormi_4 have reduced their sizes in 2009 by the mitigations measures as shown in Figure 5.14.

Fig 5.14: Mitigation measures taken for Thorthormi glacial lakes in early 2009

5.4.4 Luggye Lake

This Luggye Lake was the one of the first discovered lakes in Bhutan and in 1994 it was been outburst with the volume of 18 million cubic of catastrophic debris flow at the downstream valley. Because of its flow, it damaged the agriculture, infrastructures, livestock's and 22 people. But still rate of growth in the size of lake is constant year after year.

5.4.5 Bechung Lake

This lake was no significant in the year 1990 and it appeared 2001 and it also started increasing its size. But the area of glaciers at its head is more as compared to other like Rapstreng Glaciers. This is why, it is assumed that this Bechung Lake will be very big in near future. In 2001, there was only one Glacial Lake formation but in 2007 it shows that there were two Glacial Lakes formation with rapid increment of their Sizes but in 2009 these two were merged into one Glacial Lake.

The Figure 5.15 and Figure 5.16 indicate the variations of perimeter and area of different glacial lakes in graphical representation.

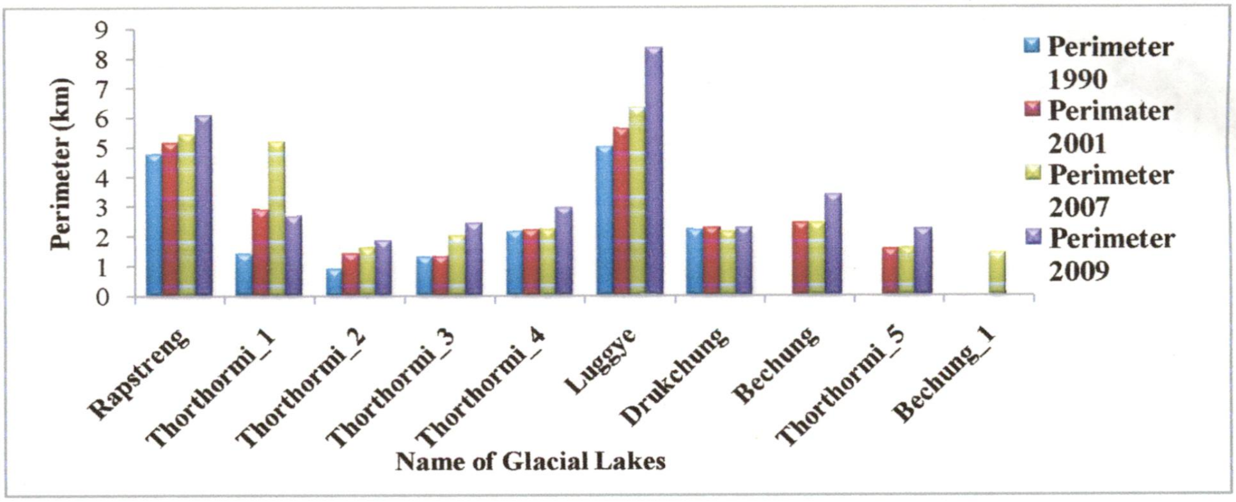


Fig 5.15: Perimeter of Glacial Lakes (1990-2009)

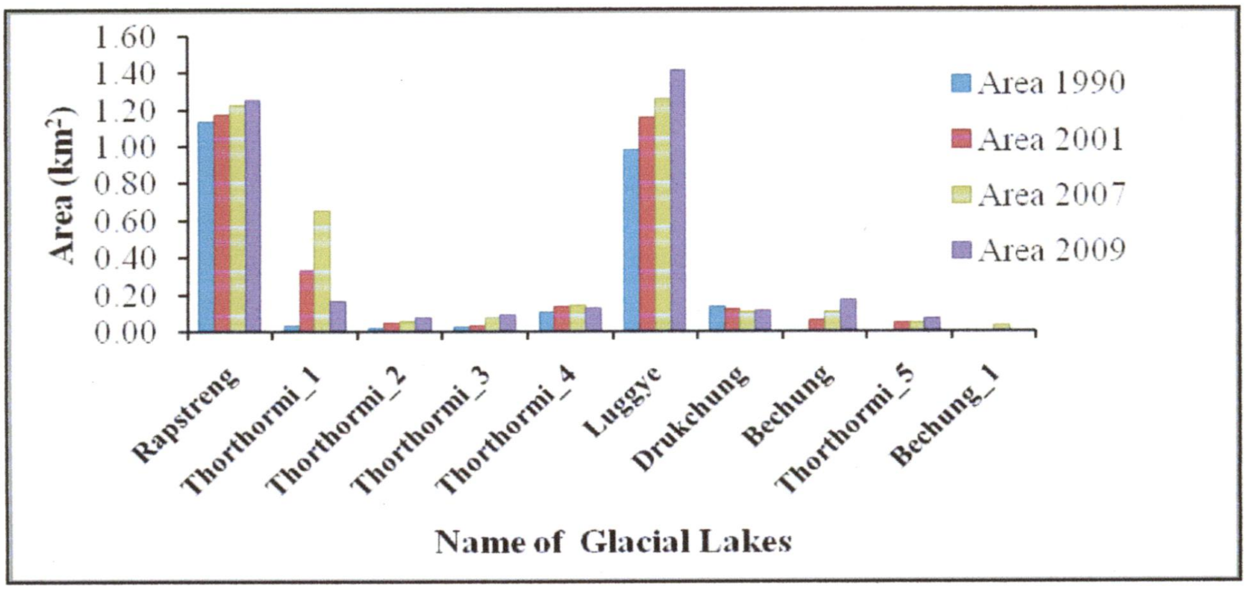


Fig 5.16: Area of Glacial Lakes (1990-2009)

The Table 5.14 shows the overall expansion of Glacial Lakes in terms of area and perimeter. It has been noticed that either in area or perimeter, the highest expansion was the Thorthomi_1 Lake. Among the Glacial lakes expansion, the highest one in the Thorthormi_1 Lake and Luggye Lake with the values 0.036 km^2 per year in each of them.The lowest one was Thorthormi_4 Lake with the values of 0.002 km^2 per year.The rate of increasing in terms of perimeter, the highest one was Thorthorthormi_1and lowest one was Thorthormi_4 Lake with the values of 0.232 km per year and 0.004 km per year respectively.

Table 5.14: Rate of variation area and perimeter for different Lakes

			Area		Perimeter	
Year	**Names of Lakes**	**Elevation (m)**	**m^2/year**	**Km^2/year**	**m/year**	**Km/year**
1990-2009	**Bechung**	4337	8680.18	0.009	-114.70	-0.115
	Rapstreng	4368	8493.37	0.008	132.75	0.133
	Thorthormi_1	4454	36119.06	0.036	231.60	0.232
	Thorthormi_2	4459	4642.96	0.005	65.42	0.065
	Thorthormi_3	4462	5104.93	0.005	96.06	0.096
	Thorthormi_4	4459	1664.90	0.002	4.42	0.004
	Thorthormi_5	4461	5985.88	0.006	160.90	0.161
	Luggye	4459	35581.19	0.036	390.75	0.39
	Drukchung	4706	-339.95	-0.0003	17.46	0.02

The Table 5.15 indicates the area of each glacial lake in particular year and Figure 5.17 shows the percentage wise. As it is shown that the highest ones are Rapstreng and luggye lakes and the Thorthormi_1 kept on increasing till 2007 but in 2009, it dropped to 5% from 17% as in Figure 5.17 and the histogram is presented in Figure 5.18. This was because in early 2009, the Royal Government of Bhutan took the mitigation measures on it as in Figure 4.14 as it gives an alarming rate of increment in volume. The department of geology and mining of Bhutan had taken the initiative for the mitigation jointly with the funding from Japan government. In the similar way, it can be observed that the total area of glacial lakes are kept on increasing from 1990 to 2007 with 2.45 km^2 to 3.73km^2 but when in 2009, it has been dropped to 3.49km^2 (Table 5.15).

Table 5.15: Total area of glacial lakes per year

Names of Glacial Lakes	**Area in km^2(1990)**	**Area in km^2(2001)**	**Area in km^2(2007)**	**Area in km^2(2009)**
Rapstreng	1.14	1.17	1.23	1.25
Thorthormi_1	0.04	0.34	0.65	0.16
Thorthormi_2	0.02	0.05	0.06	0.08
Thorthormi_3	0.03	0.04	0.08	0.10
Thorthormi_4	0.11	0.14	0.14	0.13
Thorthormi_5		0.05	0.05	0.07
Luggye	0.98	1.16	1.26	1.41
Bechung		0.06	0.11	0.17
Bechung_1			0.04	
Drukchung	0.14	0.12	0.11	0.12
Total area	2.45	3.13	3.73	3.49

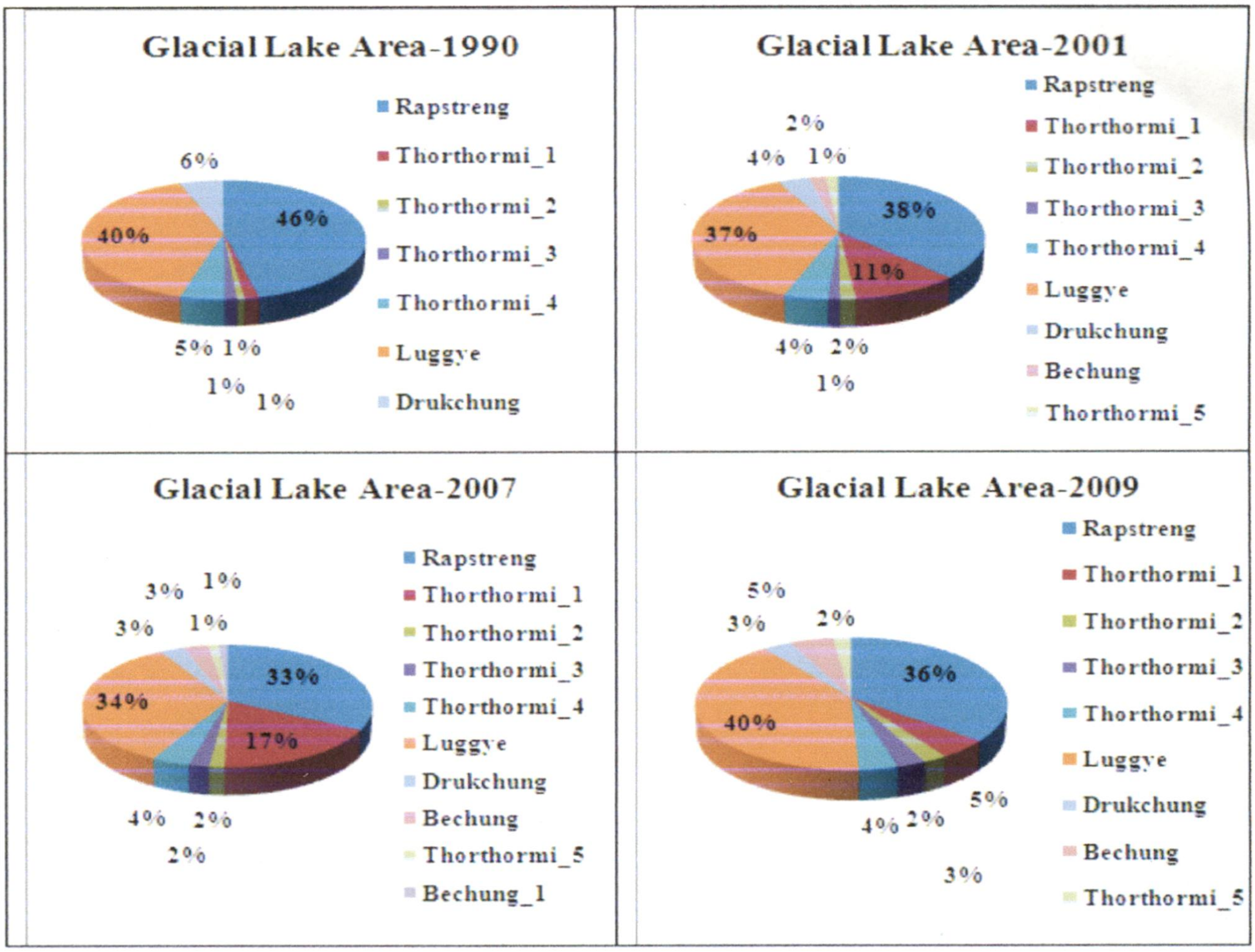


Fig 5.17: Glacial lakes area in percentage (%).

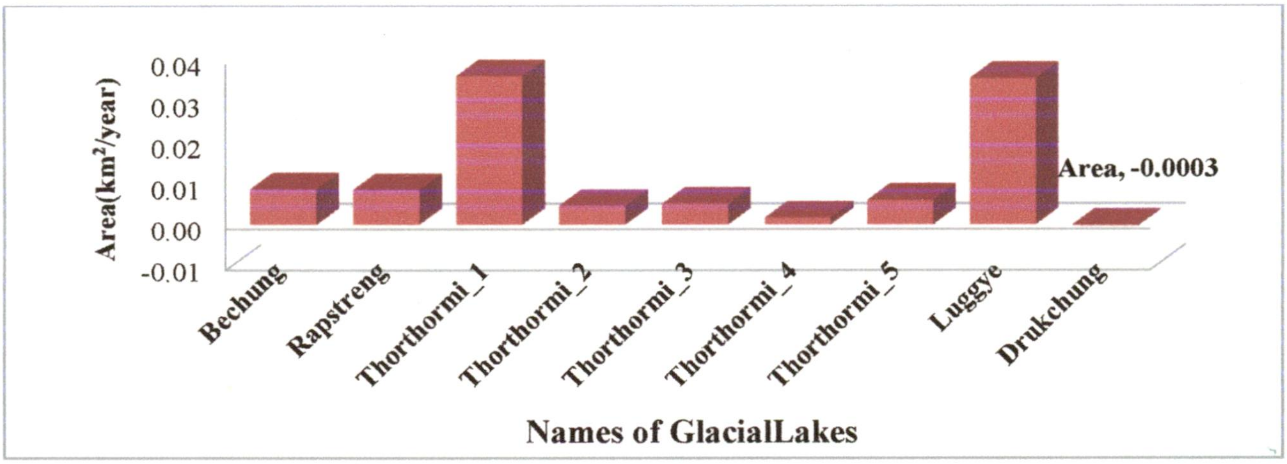


Fig 5.18: Histogram of increasing rate of Glacial Lakes area/year (1990 to 2009)

5.4.6 Expansion of Glacial Lakes in terms of Volumes.

The Table 5.16 is showing the volume increment of Glacial Lakes yearly and since there was no measurement or records of any volume of the Lake, with the help of formula given by

Huggel et al, (2002), calculations of volume was possible. So the variation of volume for each lake can be analyzed. The volume could be found out with the help of areas that were found out from the digitization of satellite maps for the different years.

Table 5.16: Volume variation glacial lake for different years

		Location			Volume of Lakes	
Year	**Names of Lakes**	**Latitude**	**Longitude**	**Elevati-onn(m)**	**m^3/year**	**Km^3/year**
1990-2001	**Rapstreng**	28'06'24.01"N	90'14'51.76"E	4368	182936.95	0.00018
	Thorthormi_1	28'06'21.78"N	90'15'48.95"E	4454	635506.07	0.00064
	Thorthormi_2	28'06'15.23N	90'15'21.95"E	4459	33106.53	0.00003
	Thorthormi_3	28'06'06.66"N	90'15'25.61"E	4462	7361.06	0.00001
	Thorthormi_4	28'05'52.78"N	90'16'05.16"E	4461	46893.28	0.00005
	Luggye	28'06'02.13"N	90'15'18.08"E	4459	825188.30	0.00083
	Drukchung	28'05'12.34"N	90'19'34.14"E	4706	-25870.99	-0.00003
2001-2007	**Bechung**	28'06'07.64"N	90'13'49..51"E	4337	118443.89	0.00012
	Rapstreng	28'06'24.01"N	90'14'51.76"E	4368	388304.15	0.00039
	Thorthormi_1	28'06'21.78"N	90'15'48.95"E	4454	1632078.39	0.00163
	Thorthormi_2	28'06'15.23N	90'15'21.95"E	4459	16560.34	0.00002
	Thorthormi_3	28'06'06.66"N	90'15'25.61"E	4462	86414.29	0.00009
	Thorthormi_4	28'05'52.78"N	90'16'05.16"E	4461	22018.68	0.00002
	Thorthormi_5	28'0602.13"N	90'15'18.08"E	4459	1079.49	0.000001
	Luggye	28'06'02.13"N	90'15'18.08"E	4459	774612.44	0.00077
	Drukchung	28'05'12.34"N	90'19'34.14"E	4706	-27583.58	-0.00003
2007-2009	**Bechung**	28'06'07.64"N	90'13'49..51"E	4337	478421.20	0.0005
	Rapstreng	28'06'24.01"N	90'14'51.76"E	4368	781529.90	0.0008
	Thorthormi_1	28'06'21.78"N	90'15'48.95"E	4454	-8034801.5	-0.0080
	Thorthormi_2	28'06'15.23N	90'15'21.95"E	4459	157007.86	0.0002
	Thorthormi_3	28'06'06.66"N	90'15'25.61"E	4462	155878.10	0.0002
	Thorthormi_4	28'0602.13"N	90'15'18.08"E	4459	-170062.00	-0.0002
	Thorthormi_5	28'05'52.78"N	90'16'05.16"E	4461	178014.87	0.0002
	Luggye	28'06'02.13"N	90'15'18.08"E	4459	4181980.21	0.0042
	Drukchung	28'05'12.34"N	90'19'34.14"E	4706	31803.25	0.00003

The Table 5.17 shows the increment in percentage for different years and the largest increment in terms of volume was found to be Thorthormi_1 Lake and some are found to be reducing their Volumes due to mitigation measures taken in 2009 like draining out the partial amount of water from the lakes.

Table 5.17: Variation of % of Volume of Lakes.

Year	Names of Lakes	Elevation(m)	Km^3	Difference in area(km^3)	increment in Volume (%)
1990	Rapstreng	4368	0.0412		
2001	Rapstreng	4368	0.0432	0.002	4.88
2007	Rapstreng	4368	0.0460	0.003	6.29
2009	Rapstreng	4368	0.0475	0.002	3.40
1990	Thorthormi_1	4454	0.0003		
2001	Thorthormi_1	4454	0.0073	0.007	2182.78
2007	Thorthormi_1	4454	0.0187	0.011	156.27
2009	Thorthormi_1	4454	0.0027	-0.016	-85.77
1990	Thorthormi_2	4459	0.0001		
2001	Thorthormi_2	4459	0.0005	0.000	300.77
2007	Thorthormi_2	4459	0.0006	0.000	23.89
2009	Thorthormi_2	4459	0.0009	0.000	52.23
1990	Thorthormi_3	4462	0.0003		
2001	Thorthormi_3	4462	0.0003	0.000	32.04
2007	Thorthormi_3	4462	0.0009	0.001	181.28
2009	Thorthormi_3	4462	0.0013	0.000	33.22
1990	Thorthormi_4	4461	0.0015		
2001	Thorthormi_4	4461	0.0020	0.001	33.71
2007	Thorthormi_4	4459	0.0022	0.000	7.53
2009	Thorthormi_4	4461	0.0019	0.000	-15.46
2001	Thorthormi_5	4459	0.0005		
2007	Thorthormi_5	4461	0.0005	0.00001	1.66
2009	Thorthormi_5	4459	0.0008	0.00036	77.06
1990	Luggye	4459	0.0334		
2001	Luggye	4459	0.0425	0.009	27.19
2007	Luggye	4459	0.0479	0.005	12.77
2009	Luggye	4459	0.0563	0.008	17.47
1990	Drukchung	4706	0.0020		
2001	Drukchung	4706	0.0017	0.000	-14.09
2007	Drukchung	4706	0.0015	0.000	-11.12
2009	Drukchung	4706	0.0016	0.000	4.12
2001	Bechung	4337	0.0007		
2007	Bechung	4337	0.0015	0.001	119.21
2009	Bechung	4337	0.0028	0.001	85.94

From the Table 5.18, it has been seen that the greatest increment rate was Thorthormi_1 and Luggye with the values of 0.0011 km^3 per year and 0.0019 km^3 per year respectively. And the lowest one was Thorthormi_4 with the value of 0.00003 km^3 per year.

Table 5.18: Rate of Increasing/decresing volume per year

		Location			Volume of Lakes	
Year	**Names of Lakes**	**Latitude**	**Longitude**	**Elevati-on(m)**	**m^3/year**	**Km^3/year**
1990 - 2009	Rapstreng	28'06'24.01"N	90'14'51.76"E	4368	450923.67	0.0006
	Thorthormi_1	28'06'21.78"N	90'15'48.95"E	4454	1133792.23	0.0011
	Thorthormi_2	28'06'15.23N	90'15'21.95"E	4459	83594.40	0.0001
	Thorthormi_3	28'06'06.66"N	90'15'25.61"E	4462	83217.82	0.0001
	Thorthormi_4	28'05'52.78"N	90'16'05.16"E	4461	34455.98	0.00003
	Luggye	28'06'02.13"N	90'15'18.08"E	4459	1927260.32	0.0019
	Drukchung	28'05'12.34"N	90'19'34.14"E	4706	-7217.10	-0.00001
2001 - 2009	Thorthormi_5	28'0602.13"N	90'15'18.08"E	4459	89547.18	0.0001
	Bechung	28'06'07.64"N	90'13'49..51"E	4337	298432.54	0.0003

Figure 5.19 tells about the amount of volume added to the particular glacial lakes in percentage and it can be seen that the highest ones are the Luggye and the Thorthormi_1 with increment of 45% and 27% respectively.

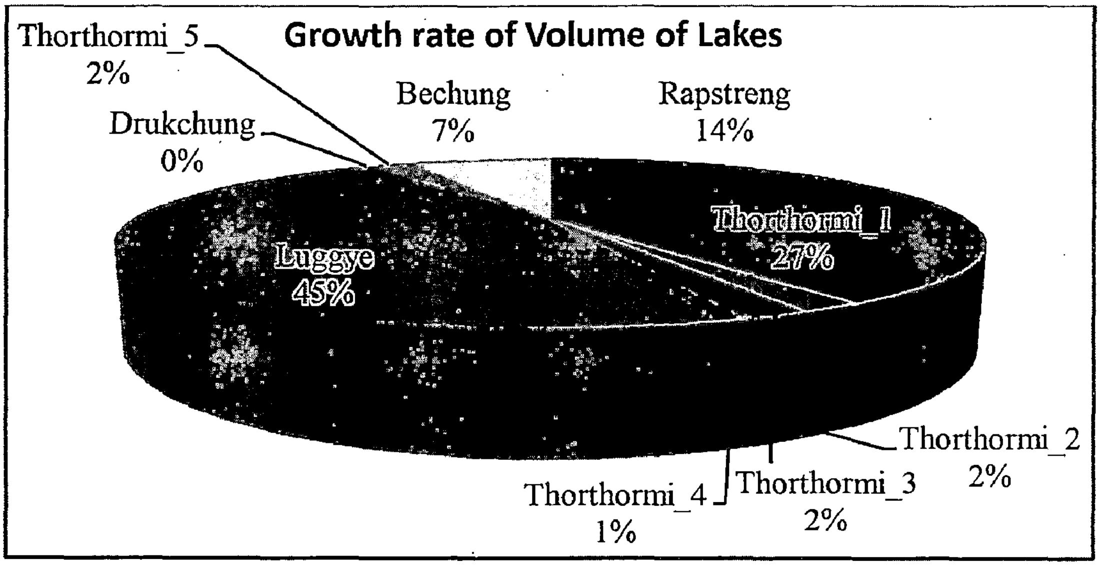


Fig 5.19: % of Volume of Lakes increment/year (1990-2009)

5.5 LAND COVER CLASSIFICATION.

In the present section land use change analysis have been presented for different years of the data set i:e 1990, 2001, 2007 and 2009. In the study area there is no settlement.

5.5.1 Land Cover Map (1990)

The land cover map of 1990, with the Histogram of the land class coverage in Figure 5.20 shows that about 38.3% was covered by snow/glacier, 22.9 % covered by Ice, 15.3% covered by forest, 18.5 % covered by grasses, 6.9% covered by barren land and 0.7 % covered by water bodies. The highest coverage was the snow/glacier and the lowest one was the water bodies and it can also be seen in Figure 5.21.

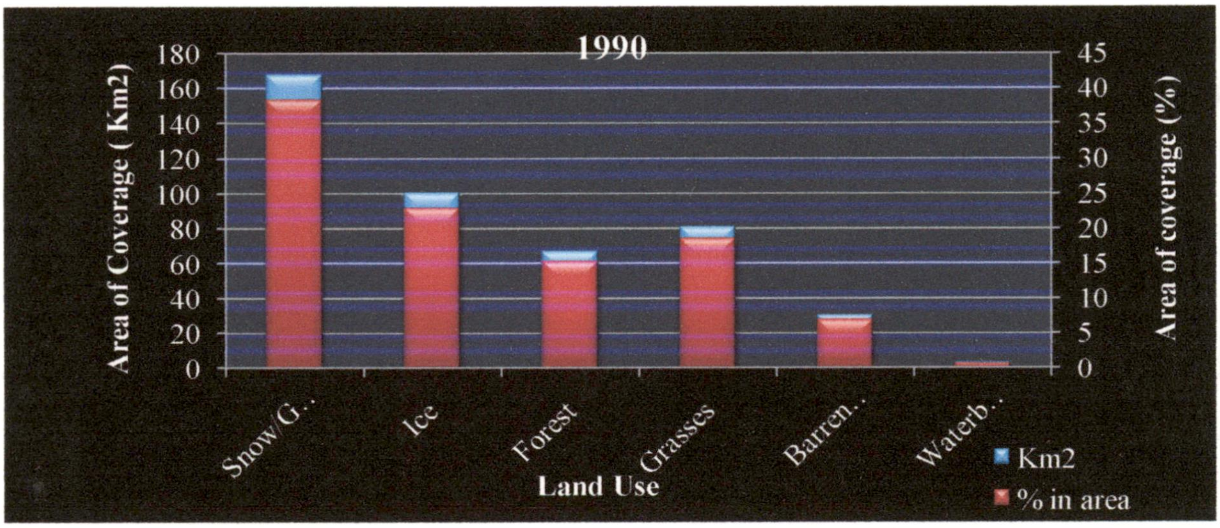


Fig 5.20: Histogram of land use covers class coverage in 1990

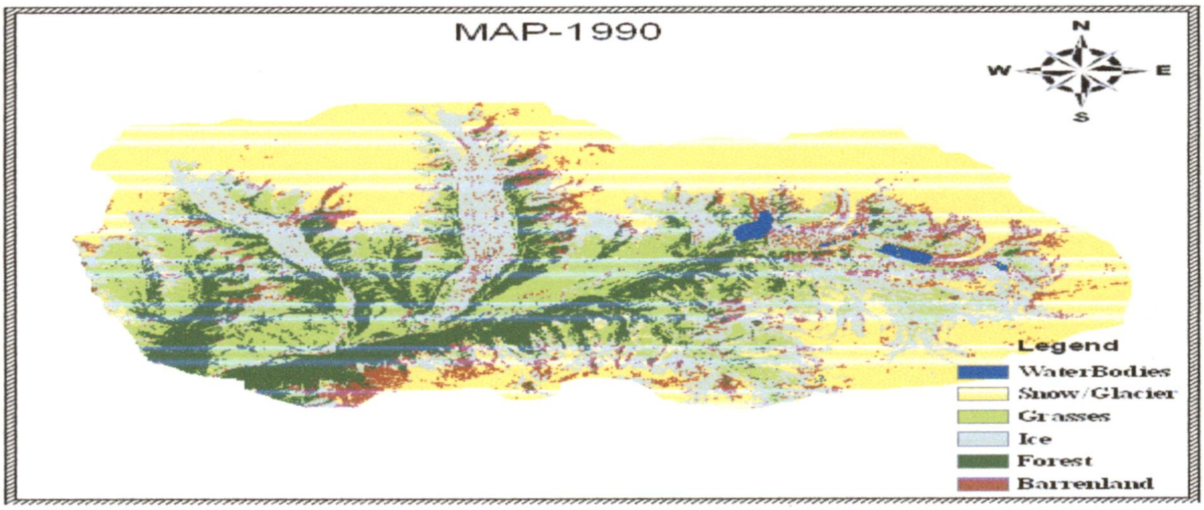


Fig 5.21: Land Cover map (1990)

5.5.2 Land Cover map (2001)

The histogram of land cover and Land Use Map of 2001 represents the following changes from 1990 to 2001 are as follows.

Snow/glacier cover is around 26.43 percent (%), Ice coverage was around 22.12 percent(%), Forest was around 27.54 percent (%), Grasses was around 19.02 percent (%), Barren land was around 2.61 percent (%) and Water bodies coverages was around 2.9 percentages (%). Therefore, the snow coverage is decreasing and water bodies are rising in quantity as shown below in Figure 5.22 and Figure 5.23.

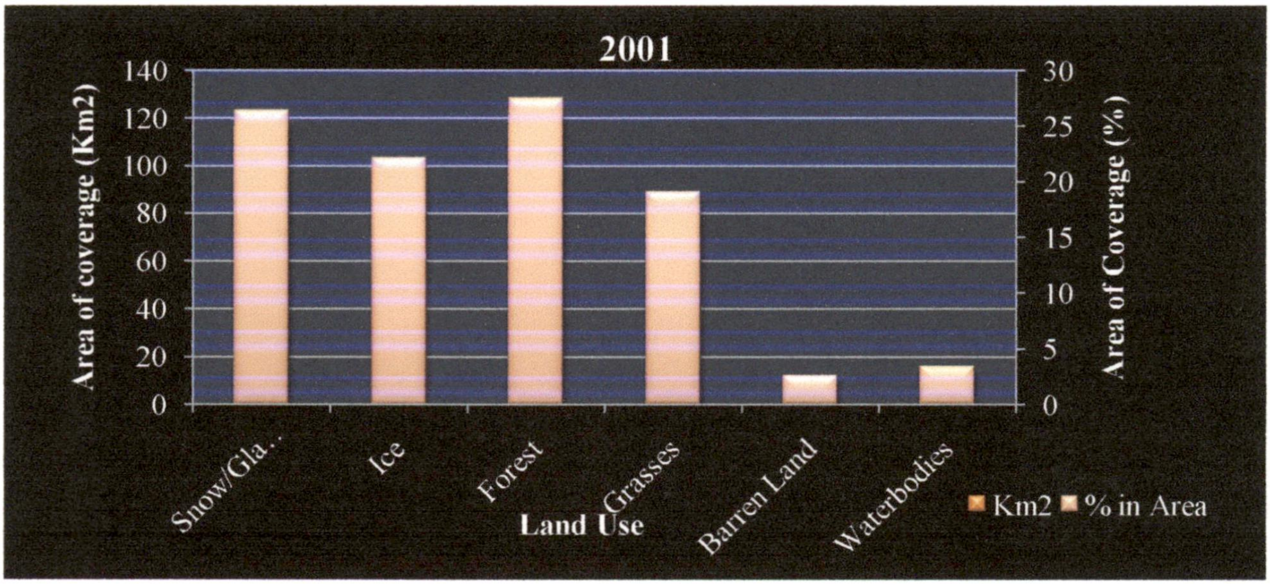


Fig 5.22: Histogram of land cover class map of 2001.

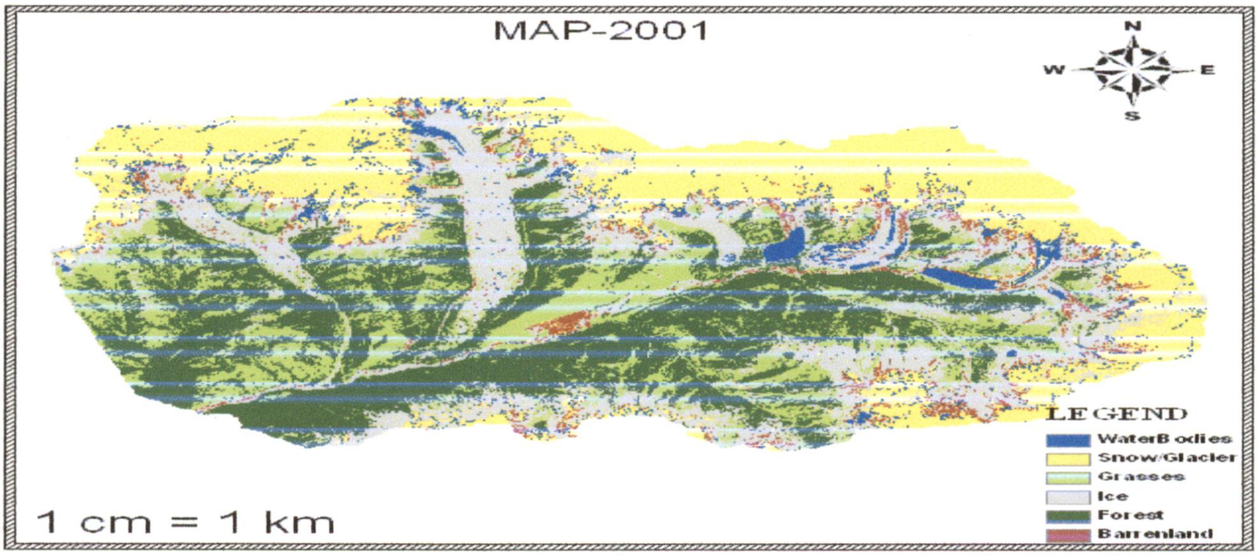


Fig 5.23: Land cover map (2001)

5.5.3 Land Cover Map (2007)

As it is seen, the changes between 1990 to2001 that the snow/glacier coverage is apparently reducing and water bodies are keep on increasing. Even forest coverage's are increasing and grass coverage's are reducing. So this may be reason due to the global warming which increases the temperature. When there is warming of temperature, there will be lengthening of growing season which may supports any kind of plants.

Now the histogram of land coverage class map and the Land cover map of 2007 is given below with the following features in Figure 5.24.

Snow/glacier coverage was around 25.56 percentages (%), Ice coverage was around 24.97 percent(%), forest coverage was around 40.34 percent (%), grasses coverage was 5.38 percent (%), barren land coverage was around 5.97 percent (%) and water bodies was around 3.85 percent (%). And still we see some changes between the map of 2001 to 2007 and it is shown in Figure 5.25.

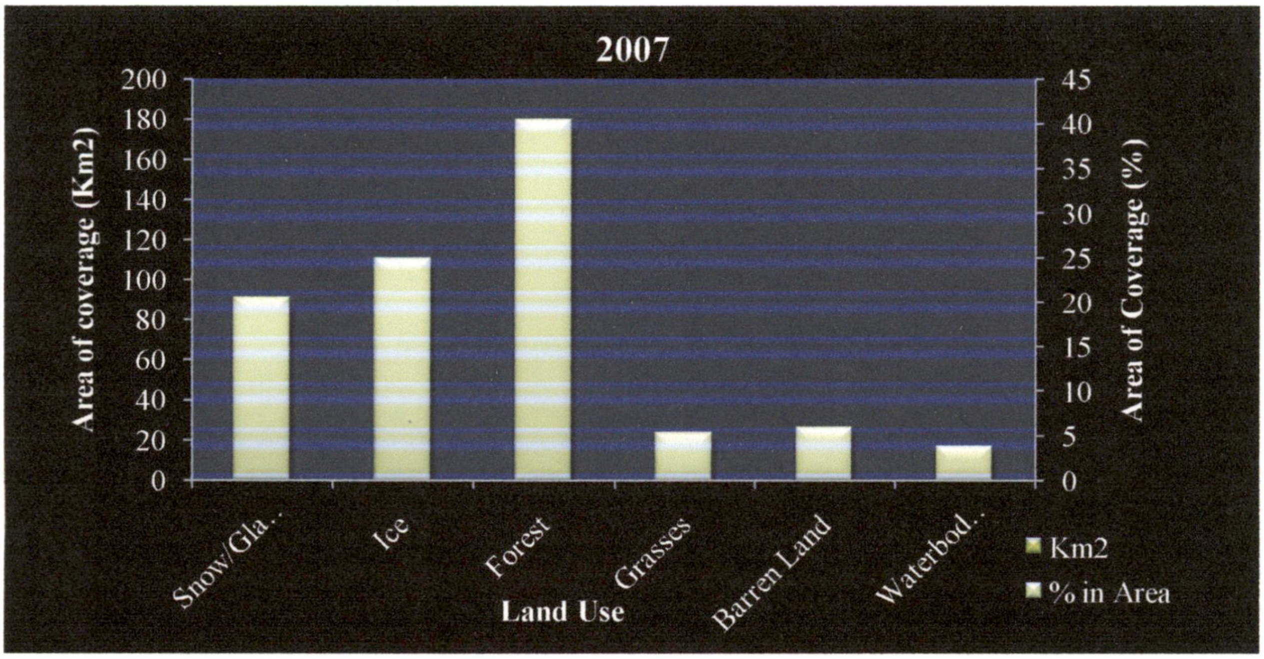


Fig 5.24: Histogram for the Land use covers of 2007.

Comparatively we can see from the map that snow coverage was kept on reducing in terms of area when it is compared to 2001 map, water bodies were more and forest density was increasing as seen in Figure 5.25.

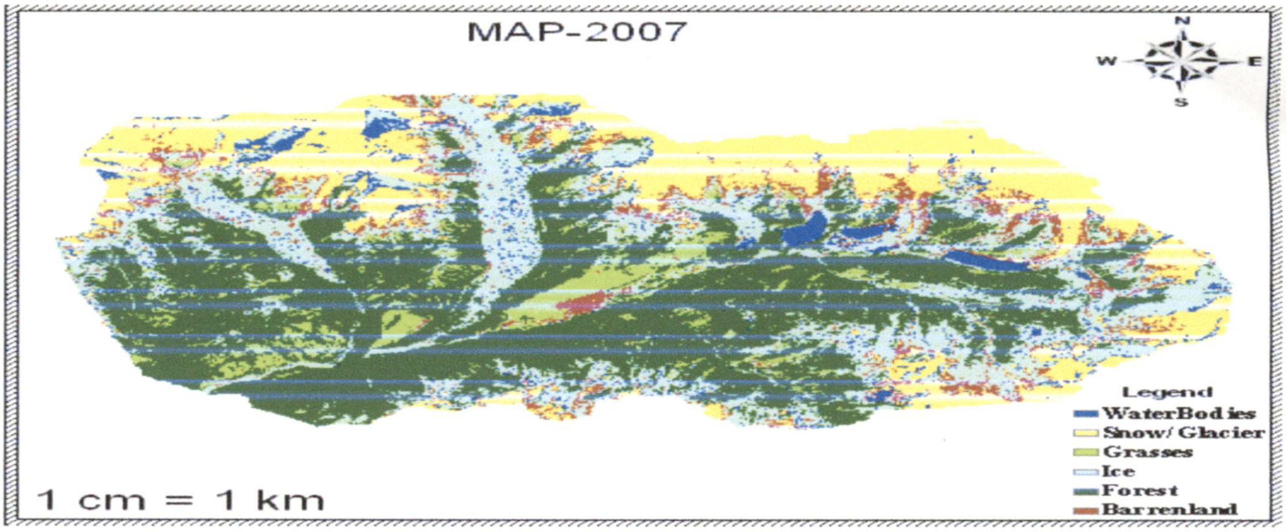


Fig 5.25: Land cover map (2007)

5.5.4 Land Use Cover (Year -2009)

The map of 2009 was given with its histogram (Figure 5.26) of Land use map and it is noticeable that there was a still change from 2007 which was only two years of gap. The land cover map for 2009 is shown in Figure 5.26. The three things like snow/glacier cover, water bodies and forest are changing year after year. The histogram of land use and Land cover map of 2009 are given with the following features.

Snow coverage was around 16.65 percent(%), Ice coverage was around 20.68 percent(%), forest coverage was around 40.12 percent(%), grasses coverage was 5.88 percent(%), barren land coverage was around 10.97 percent(%) and water bodies was around 8.28 percentag(%)

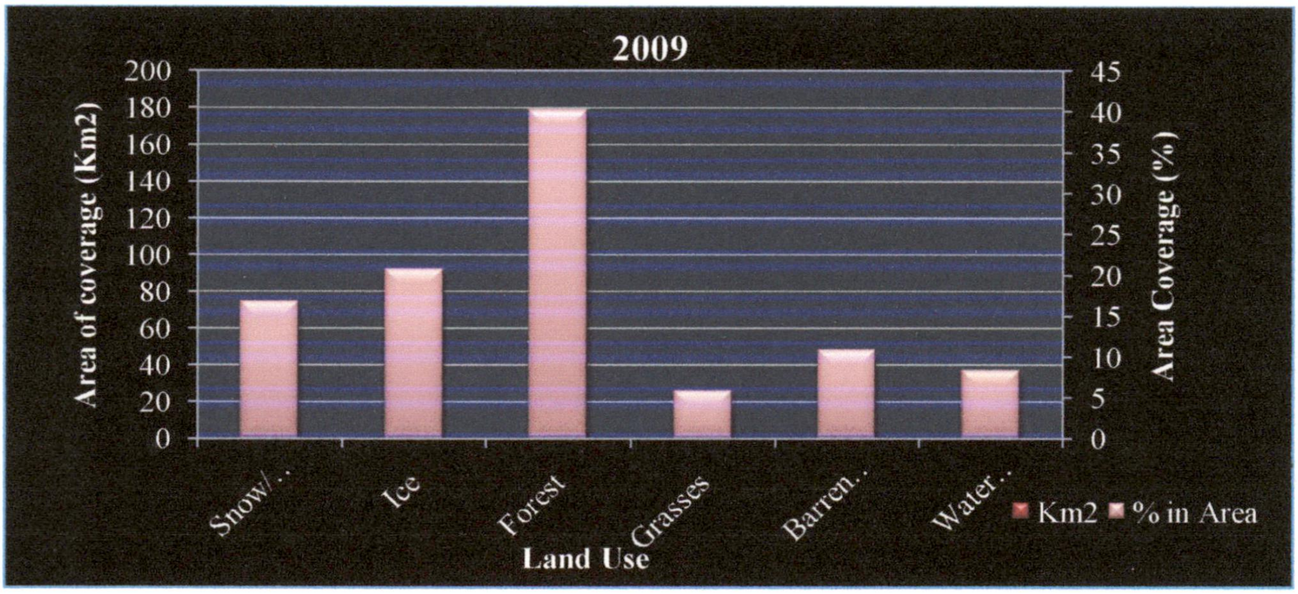


Fig 5.26: Histogram of Land use coverage (2009)

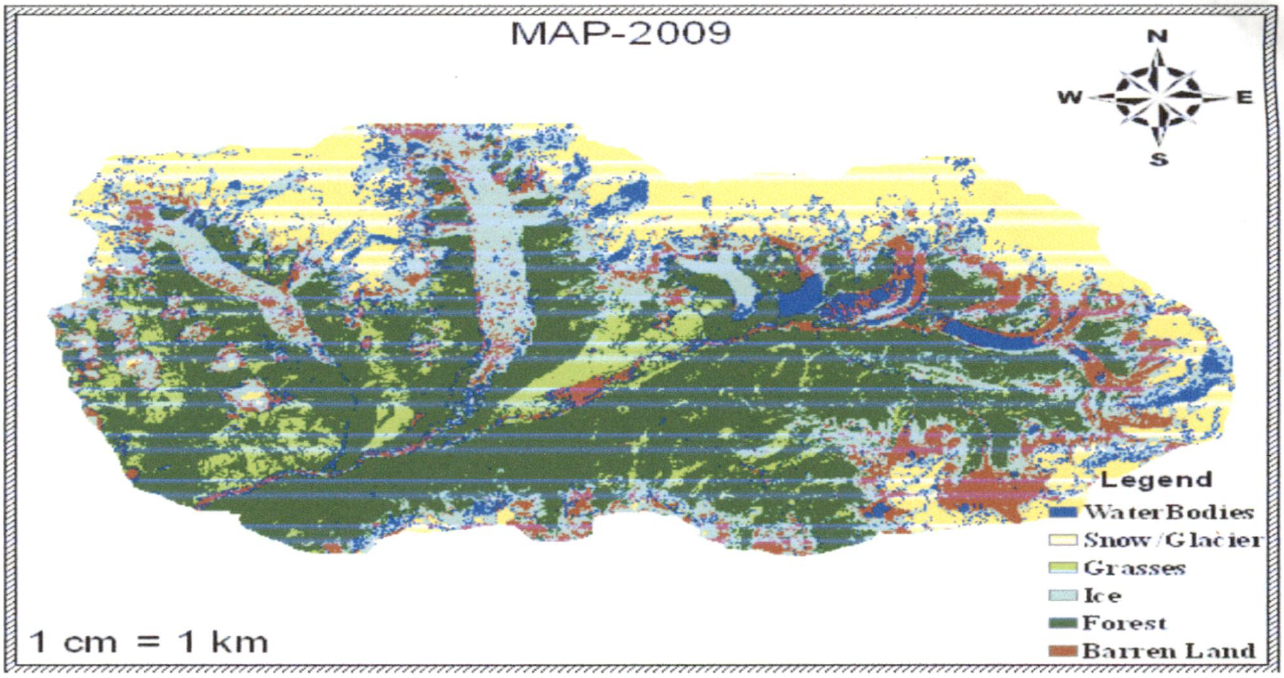


Fig 5.27: Land coverage map (2009)

Summary of Land Cover Class

In this study area, there are four maps of different years which were generated for the land cover classification. Satellite data used for the reference years 1990, 2001, 2007 and 2009 have been used in the study. So for each year class areas and its percentages are represented in the Table 5.19 for the same and statistics changes for the period 1990- 2009 are summarized in Table 5.19 and Table 5.20 respectively.

Table 5.20 shows the negative and positive signs indicating the decrease and increase respectively for land cover classes for the specific year. Among the land cover changes, three of them are constantly changing like snow, forest and water bodies. From the year 1990 to 2001, the snow coverage decreases was around -1.05 % per year, while the forest area was increased by 1.09% per year and the water bodies were increased by 0.26% per year. The year from 2001 to 2007, snow coverage was decreased by -0.82% per year, while forest was increased by 1.8% per year and water bodies was increased by 0.1% per year.

Lastly for the period from 2007 to 2009, snow coverage was decreased by -1.26 % per year, while forest was almost same as before and water bodies was increased by 1.4% per year. And the other land covers were having some variation either increasing or decreasing. The Table 5.21 indicates the variations of areas for the different years.

Table5.19: Summary of Land Use Cover type in the Lunana region

	1990		2001		2007		2009	
Land Use	**Km^2**	**% in area**	**Km^2**	**% in area**	**Km^2**	**% in area**	**Km^2**	**% in area**
Snow/Glacier	167.50	38.30	115.6	26.43	89.90	20.56	72.80	16.65
Ice	99.90	22.90	96.75	22.12	109.21	24.97	90.45	20.68
Forest	66.80	15.30	120.44	27.54	176.78	40.43	175.46	40.12
Grasses	80.70	18.50	83.19	19.02	23.53	5.38	25.71	5.88
Barren Land	30.00	6.90	11.40	2.61	26.09	5.97	47.18	10.79
Water bodies	2.90	0.70	14.96	3.42	16.83	3.85	36.19	8.28

Table 5.20: Summary of land Cover type Change in the Lunana region (%)

	1990 -2001		2001-2007		2007-2009		1990-2009	
Land Use	**Km^2**	**% in area**	**Km^2**	**% in area**	**Km^2**	**% in area**	**Km^2**	**% in area**
Snow/Glacier	-51.90	-11.60	-25.71	-5.70	-17.07	-3.80	-94.63	-21.10
Ice	-3.20	-0.70	12.46	2.80	-18.76	-4.20	-9.48	-2.10
Forest	53.70	12.0	56.35	12.60	-1.32	-0.30	108.68	24.30
Grasses	2.50	0.50	-59.66	-13.30	2.18	0.50	-55.02	-12.30
Barren Land	-18.60	-4.10	14.69	3.30	21.09	4.70	17.23	3.80
Waterbodies	12.10	2.70	1.87	0.40	19.36	4.30	33.29	7.40

The Table 5.21 indicates the overall increment and decrement of the land cover of Lunana region from the 1990 to 2009 for 21 years.

Table 5.21: Rate of variation of land Cover

	1990-2009	
Land Use	**Km^2/Year**	**% in area/year**
Snow/Glacier	-4.51	-1.0
Ice	-0.45	-0.1
Forest	5.18	1.2
Grasses	-2.62	-0.6
Barren Land	0.82	0.2
Water bodies	1.59	0.4

5.6 SUMMARY OF CLIMATE CHANGE ON GLACIERS/GLACIAL LAKES

The summary of the overall results of Glaciers, Glacial Lakes and Land cover mapping correlating with temperature are presented in Table 5.22, Table 5.23 and Table 5.24 respectively. It has been noticed that there is obvious changes from the year 1990-2009 which can be seen in Table 5.22, Table 5.23 and Table 5.24.

Table 5.22: Correlation of temperature with Glaciers

Items/Descri-ption	Temperature increasing (1990 -2009) per year	Decreasing rate of Thickness of Glaciers (m/year)	Retreating rate of Glaciers in terms of area (Km^2/year)	Retreating Rate of Glaciers (m/year)
Glaciers:				
1/Bechung	0.043	1.09	0.178	15.26
2/ Rapstreng	0.043	0.99	0.112	32.15
3/**Thorthormi**	0.043	0.99	**0.196**	**35.27**
4/Luggye	0.043	1.01	0.2	23.495

Table 5.23: Correlation of temperatures with Glacial Lakes

Items/Descri-ption.	Temperature increasing (1990 -2009) per year	Area Expansion Rate of Glacial Lakes km^2/year)	Perimeter expansion rate of Glacial Lakes (km/year)	Volume Expansion rate of Glacial Lakes (km^3)
Glacial Lakes				
1/Bechung	0.043	0.009	-0.115	0.0003
2/Rapstreng	0.043	0.008	0.133	0.0006
3/**Thorthormi_1**	0.043	**0.036**	**0.232**	**0.0011**
4/Thorthormi_2	0.043	0.005	0.065	0.0001
5/Thorthormi_3	0.043	0.005	0.096	0.0001
6/Thorthormi_4	0.043	0.002	0.004	0.00003
7/Thorthormi_5	0.043	0.006	0.161	0.0001
8/Luggye	0.043	0.036	0.39	0.0019
9/Drukchung	0.043	-0.0003	0.02	-0.00001

Generally, there are two types of Glaciers, D_type and C-type. The D_type is for Glaciers mixed with debris whereas the C_type is the clean Glaciers and it is said that clean Glaciers (C_tpes) are more prone to be melted at a faster rate than those of D_types. As shown in Tables (5.22 and 5.23), there is an increased of 0.043°c per year for the last 15 years and it is noticed that it affects more to the Glaciers and Glacial Lakes of Thorthormi showing the faster rate of melting as compared to others. In the similar way, it is noticed that in every respect in terms of Decreasing thickness, area expansion, retreating rate of Glaciers are showing faster rate. Therefore it can be said that Thorthormi Glaciers are the C_types of Glaciers and Bechung Glaciers are of D-types from the Table 5.22 and Table 5.23.

5.7 EFFECT OF CLIMATE CHANGE/GLACIERS MELTS IN LAND COVER

With time from 1990-2009, the effects of temperature and Glaciers melting resulted with the following features. The negative values indicate retreated and positive value indicates increasing rate. It has been observed that the Snow cover was retreating and water bodies were increasing rate with -1.0% per year and 0.4% per year respectively as shown in Table 5.24.

Table 5.24: Correlations with Land Cover Mapping

	1990-2009		
Land Use (watershed)	**Temperature(°C) increment/year**	**Km^2/Year**	**% in area/year**
Snow /Glaciers	0.043	-4.51	-1
Ice	0.043	-0.45	-0.1
Forest	0.043	5.18	1.2
Grasses	0.043	-2.62	-0.6
Barren Land	0.043	0.82	0.2
Water bodies	0.043	1.59	0.4

5.8 WATERSHED DELINEATION FROM ARCH HYDRO TOOL.

DEM Reconditioning

The DEM Reconditioning function (DEM Manipulation menu) modifies Digital Elevation Models (DEMs) by imposing linear features onto them (burning/fencing). This function is an implementation of the AGREE method developed by Ferdi Hellweger at the University of Texas at Austin in 1997.

Fill Sinks

The Fill Sinks function (DEM Manipulation menu) fills sinks in a grid. If a cell is surrounded by higher elevation cells, the water is trapped in that cell and cannot flow. The Fill Sinks function modifies the elevation value to eliminate these problems.

A Deranged Polygon feature class may be specified to define areas that should not be filled. A threshold may also be specified – in those cases only sinks, whose depth is lower than the threshold, will be filled.

Flow Direction

The Flow Direction function (Terrain Preprocessing menu) takes a grid ("Hydro DEM" tag) as input, and computes the corresponding flow direction grid ("Flow Direction Grid" tag). The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell.

If an Outer Wall Polygon is specified, the resulting Flow Direction Grid will be masked to this feature class. This allows getting rid of the expanded extent created by the Build Walls Function.

Flow Accumulation

The Flow Accumulation function (Terrain Preprocessing menu) takes as input a flow direction grid ("Flow Direction Grid" tag). It computes the associated flow accumulation grid ("Flow Accumulation Grid" tag) that contains the accumulated number of cells upstream of a cell, for each cell in the input grid.

Stream Definition

The Stream Definition function (Terrain Preprocessing menu) takes a flow accumulation grid ("Flow Accumulation Grid" tag) as input and creates a Stream Grid ("Stream Grid" tag) for a user-defined threshold. This threshold is defined either as a number of cells (default 1%) or as a drainage area in square kilometers.

Stream Segmentation

The Stream Segmentation function (Terrain Preprocessing menu) creates a grid of stream segments that have a unique identification. Either a segment may be a head segment, or it may be defined as a segment between two segment junctions. All the cells in a particular segment have the same grid code that is specific to that segment.

Catchment Grid Delineation

The Catchment Grid Delineation function (Terrain Preprocessing menu) creates a grid in which each cell carries a value. The value corresponds to the value carried by the stream segment that drains that area, defined in the input Link grid.

Catchment Polygon Processing

The Catchment Polygon Processing function (Terrain Preprocessing menu) takes as input a catchment grid ('Catchment Grid" tag) and converts it into a catchment polygon feature class ("Catchment" tag).

Drainage Line Processing

The Drainage Line Processing function (Terrain Preprocessing menu) converts the input Stream Link grid into a Drainage Line feature class. Each line in the feature class carries the identifier of the catchment in which it resides.

After complete setting all the parameters described above, the study map of watershed, sub-basin and stream network restricted to the watershed was obtained when the interface has completed as shown in Figure 5.28.

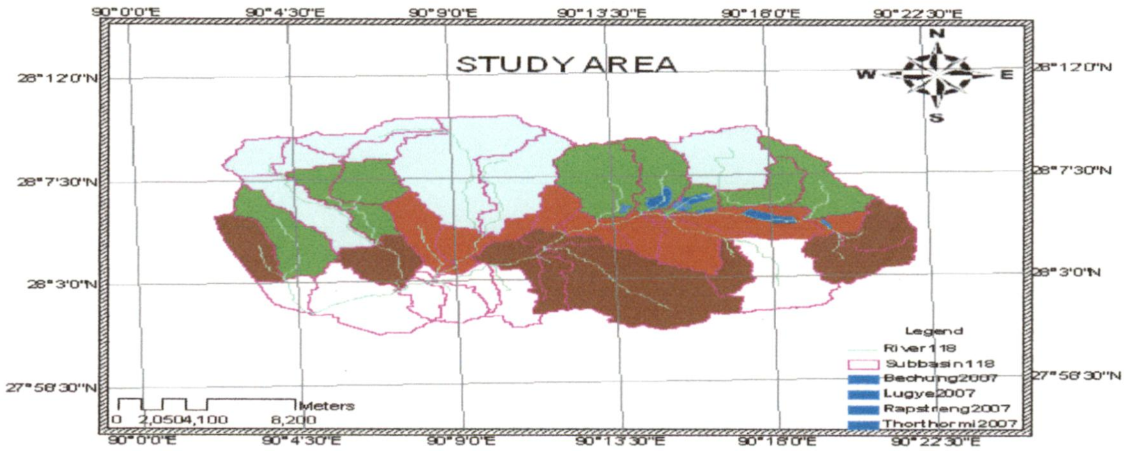


Fig 5.28: Watershed catchment area delineated.

The Table 5.25 shows the watershed characteristics for the study area and it gives the details of Sub-basins(W), area of sub-basins (Acre), slope of basins length of river reach(R) and slope of rivers and there are 47 sub-basins in this watershed area.

Table 5.25: Watershed characteristics of study area

Basin			River			Basin			River		
NAME of Sub-Basin	**Shape Area (Basin-Acre)**	**Basin Slope**	**Name of Reach**	**Slope of River**	**River Length (m)**	**Name of Sub-Basin**	**Shape Area (Basin-Acre)**	**Basin Slope**	**Name of Reach**	**Slope of River**	**River Length (m)**
W490	2010.3	0.18	R30	0.31	3899.9	W730	1086.39	0.74	R220	0.06	2108.8
W500	1133.7	0.46	R20	0.20	1143.1	W740	792.72	1.28	R210	0.03	2079.0
W510	8625.0	0.31	R180	0.03	9929.5	W750	2261.86	1.28	R340	0.05	4388.4
W520	4503.2	0.30	R60	0.28	4917.5	W760	872.60	0.67	R270	0.03	1821.6
W530	1663.0	0.11	R40	0.08	1361.1	W770	2372.97	0.53	R350	0.14	3508.2
W540	4957.8	0.50	R190	0.05	8531.0	W780	2145.77	0.27	R260	0.17	1854.7
W550	1168.0	0.54	R50	0.03	344.25	W790	2663.97	1.04	R400	0.05	4971.1
W560	3333.6	0.69	R230	0.06	8361.1	W800	3075.65	0.24	R320	0.10	2861.0
W570	3108.6	0.24	R100	0.11	4711.4	W810	1420.11	0.75	R290	0.15	1639.5
W580	4747.1	0.27	R140	0.09	5130.0	W820	9403.00	0.17	R480	0.09	9292.0
W590	3309.5	0.50	R160	0.22	4308.0	W830	350.19	0.74	R280	-0.03	551.27
W600	1294.0	0.41	R70	0.09	2173.5	W840	1183.52	0.31	R310	0.00	2622.4
W610	2464.1	0.48	R80	0.09	1236.2	W850	1331.60	0.26	R300	0.22	1003.9
W620	1091.3	0.69	R120	0.02	3371.7	W860	1524.89	0.92	R440	0.08	5859.7
W630	2240.2	0.47	R90	0.09	4464.6	W870	4975.64	0.41	R380	0.06	3065.0
W640	1248.0	0.95	R240	0.06	3653.7	W880	1952.48	0.22	R430	0.18	2819.6
W650	3998.4	0.82	R360	0.09	5882.8	W890	129.88	3.15	R370	0.11	619.31
W660	185.25	1.19	R110	0.06	1201.2	W900	1281.98	0.70	R450	0.15	3575.0
W670	3056.4	0.53	R170	0.03	6952.7	W910	147.32	1.07	R390	0.05	503.16
W680	1467.6	0.64	R150	0.06	2388.1	W920	1141.56	0.35	R410	0.04	1783.1
W690	8.05	3.39	R130	0.03	150.7	W930	1338.50	0.36	R420	0.24	1762.4
W700	2748.2	0.63	R250	0.08	3850.6	W940	4636.56	0.39	R460	0.02	4729.2
W710	2296.5	0.97	R330	0.10	4551.9	W950	8.24	2.35	R470	0.09	176.20
W720	1304.0	1.03	R200	0.33	1258.4						

The Figure 5.29 shows that the Curve number of the study area of watershed delineation and the highest one are the 70-100 numbers which indicates that those area are of cover by Glacier and barren land. Each <u>sub catchment</u> uses a Curve Number (CN) to characterize the runoff properties for a particular soil and ground cover. The CN value is a primary input parameter for the SCS runoff equation, as used by Hydro CAD.

High CN values (such as 98 for pavement) cause most of the rainfall to appear as runoff, with minimal losses. Lower values (such as 58 for certain wooded areas), correspond to an increased ability of the soil to retain rainfall, and will produce much less runoff.

The curve number is based on the hydrologic soil group and ground cover. The sub catchment entry screen in Hydro CAD includes a "Lookup" button that lets you browse a table of CN values that is based on the TR-55 reference table.

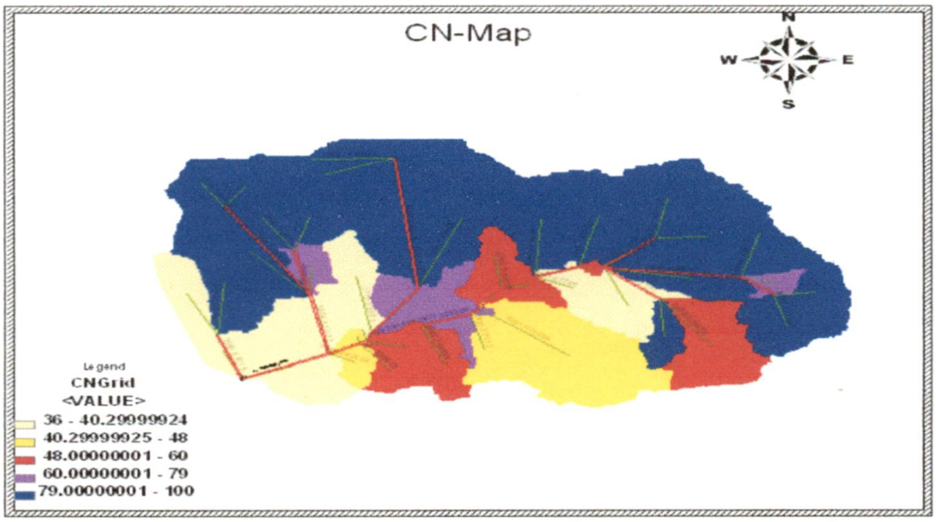


Table 5.29: CN _number for study area

5.9 UNSTEADY FLOW ANALYSIS OF POCHU RIVER.

It has been analyzed on the basis of only water surface profile as the river does not have the cross-sections measurements. The cross sections were being extracted from the HEC-GeoRAS and it is one of the extension tools for the GIS. With the help of Digital Elevation Model, converting it into Triangulated Network System (TIN), cross section can be drawn on it and were exported to the HEC-RAS. The following Figure 5.30 indicates the River, the Storage of Lakes and cross section of river around 20 km length.

The Table 5.26 shows the every five years of interval of volumes and discharges of Rapstreng glacial lakes considering the increment of lake per year would be 450923.67 m^3. These are the input data for the unsteady flow analysis.

$$Q_{max}=179(V_O*10^{-6})^{0.64}$$

Table 5.26 : Input data for HEC-RAS

Name of Glacial Lakes	Rate of increment/year=450923.67 m3	2009	2014	2019
Rapstreng	Volume, Vo (m^3)	47519129.9	49773748.2	52028366.6
Rapstreng	Peak Discharge (m^3s-1),	2118.60	2182.39	2245.16
	ft cubic/second	74786.56	77038.52	79254.05

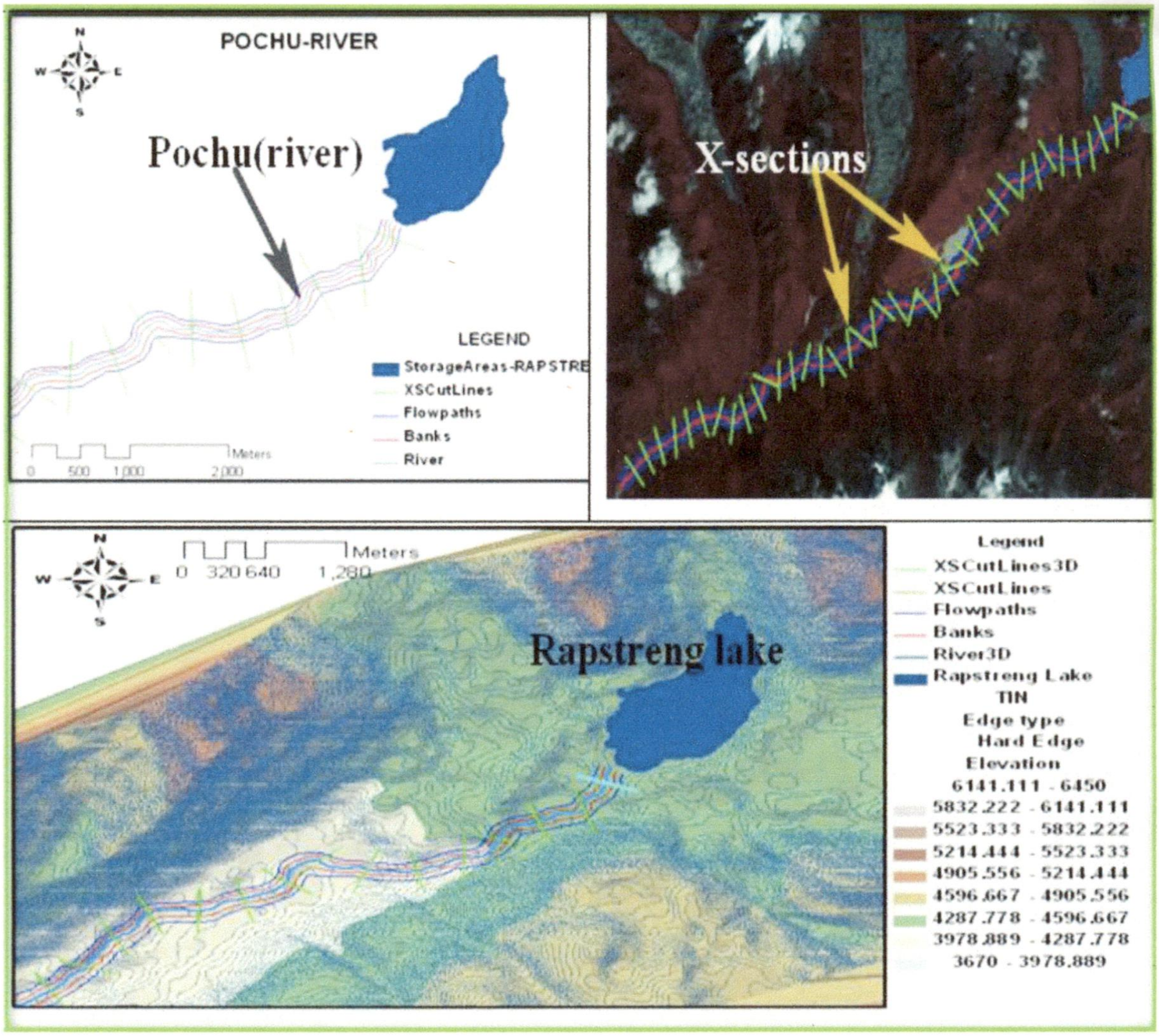


Fig 5.30: Cross-sections of River Pochu.

5.9.1 Water surface profile in HEC-RAS and cross-section of river.

The following figure 5.31 is water surface profile of river at the first stage of out bursting mechanism whereas the last water surface profile of river at the last stage of outburst is shown in Figure 5.32. It indicates the water surface level rises abruptly at the first cross section at A of the river and then keeps on lowering the water surface. When it reaches to middle cross-section, the water tends to flood over the channel as the slope of the river becomes lower and flatter. As it is seen that cross-sections at B and C are flooding over the channels and also it is seen in Figure 5.33 at cross-section C, the cross-section is mount up at the middle, it is because of deposition of sediments at that place.

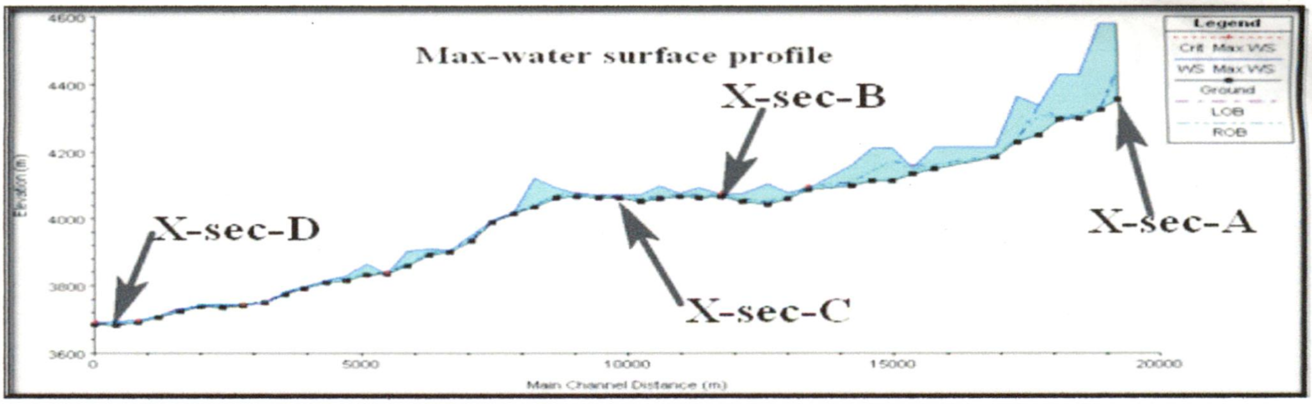


Fig 5.31: River profile at the first stage of Outburst.

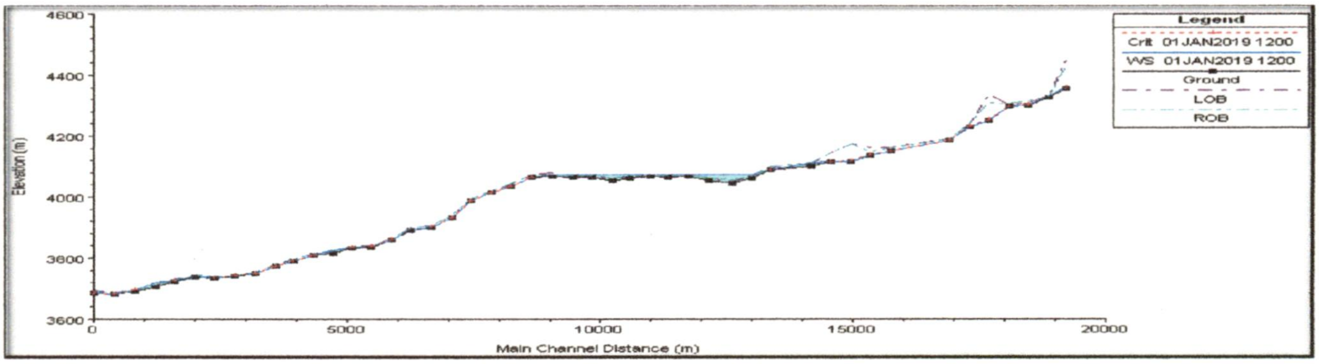


Fig 5.32: River profile at the last stage of Outburst.

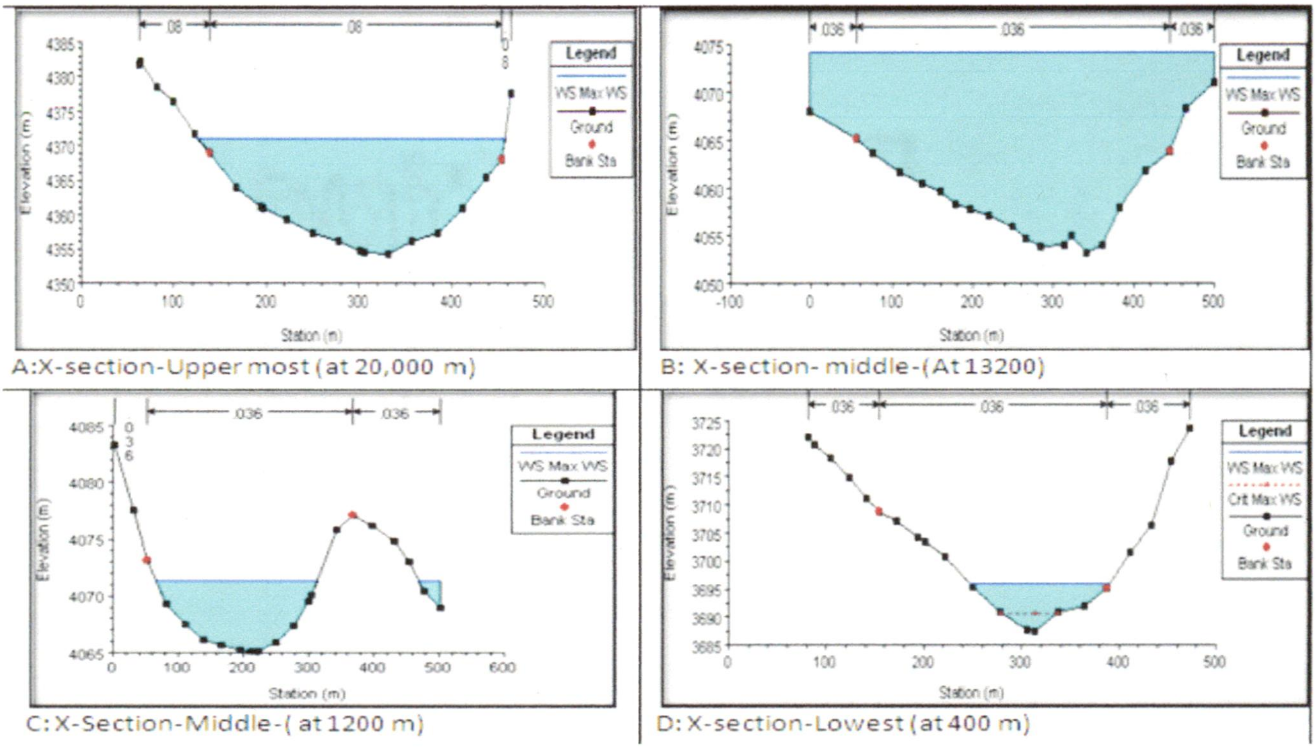


Fig 5.33: Four Cross-sections of river at different places.

The Table 5.27 shows the general characteristics of River (Pochu). It shows the variations of discharges at different locations, flow area variation at different locations and water surface elevation at different locations. Figure 5.34 indicates the comparison of water surface elevation (m) and flow area in m^3/sec throughout the length of river.

Table 5.27: General Characteristics of River Pochu by HEC-RAS

Reach length (m).	Q(m3/sec)	Min.cha. elevation (m)	Water surface elevation (m)	Flow area (m2)	Top with (m)	Reach length (m).	Q(m3/sec)	Min.cha. elevation (m)	Water surface elevation (m)	Flow area (m2)	Top with (m)
20000	2500	4356.9	4700.3	106405.8	313.9	9200	41	4065.4	4072.8	654	153
19600	1556.4	4326.4	4361.5	10509.2	343.6	8800	184.7	4034.9	4039.2	224.9	105.2
19200	2667.1	4300.1	4361.4	17878.5	337.6	8400	234	4014.8	4031.3	2366.9	212.4
18800	1565.5	4296.7	4361.4	19017.5	332.7	8000	1380	3987	3988	23.1	37.9
18400	492.4	4250.3	4361.4	28327.4	273.8	7600	460	3931.6	3934.8	225.6	98.3
18000	13366	4230.4	4246.8	2975.1	299.1	7200	1350	3900.7	3906	457.4	146.6
17600	218.9	4184.6	4189.7	773	255.2	6800	250	3892.4	3893.9	86.8	99.9
16400	2404.5	4149.7	4173.3	7465.7	390.1	6400	29.8	3859.2	3866.6	1310.2	287.7
16000	780.1	4136.7	4173.3	12248.3	400	6000	234	3836.1	3837.5	115.1	114.6
15600	861.3	4116.1	4169	9229.5	195.3	5600	1600	3832.2	3834.4	73.2	54.3
15200	283.9	4114.5	4169	8597.5	178.8	5200	264.8	3815.1	3825	1187	210.2
14800	51.1	4101.1	4117.8	2460.5	254.7	4800	27.4	3808.8	3809.9	47.4	70.1
14000	1500	4088.6	4090.1	172.8	153.2	4400	13.2	3792	3797.6	810.1	257.2
13600	130.3	4062.2	4073.3	2416.8	336.2	4000	8.3	3772.8	3777.5	493	178
13200	23.8	4044.3	4073.3	9342.2	385.2	3600	169.8	3749.4	3751.7	208.1	132.9
12800	12.5	4054	4074	4071.4	276.4	3200	209.6	3742.3	3743.2	90	169.6
12400	257.1	4068	4073.4	928.3	284.5	2800	7.4	3735.3	3736.3	51.5	81.5
12000	298.4	4065	4073.5	2091.8	405.9	2400	84.3	3738	3740.6	221.7	135
11600	316.3	4066.8	4073.5	1356.5	281.4	2000	119.4	3724.9	3727	134.7	95.4
11200	302.9	4062.8	4073.6	1325.8	201.6	1600	9.2	3704.8	3723.1	2190.9	182.3
10800	278.5	4054.3	4073.7	5631.9	400	1200	138	3692.1	3696.7	258.5	107.5
10400	219	4064.7	4073.7	4895.1	882.6	800	1144	3681.8	3688.3	1072.9	217
10000	875.5	4064.7	4080.5	4969.6	396	400	1451	3686	3694.3	757.2	153
9600	54.4	4067	4073.8	946.5	200.2						

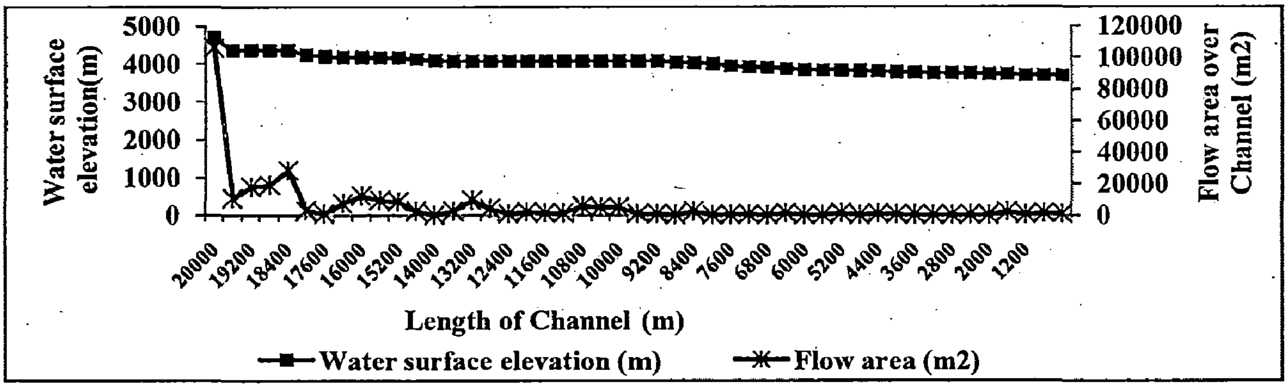


Fig 5.34: Water surface elevation and flow area throughout the length of River

5.10 CONCLUDING REMARKS

The summary of on overall results on glaciers, glacial lakes and land use, indicate that there is a definite change with climate change. With an increment of temperature of 0.043°C per year from 1996 to 2009, there is a reduction of glaciers thickness about 0.99 meter per year with lowest of Rapstreng glaciers and 1.01meter per year with highest of Luggye glaciers. The retreating rates in terms of meter per year were Thorthormi glaciers with 35.27 meter per year and in terms of areal reduction, the highest ones were Thorthormi glaciers and Luggye glaclers. Thus, the change in glacier area more from 2001 to 2009 than from 1990 to 2001 although there is less duration of years in later one.

Correspondingly, the glacial lakes too have been expanded year after year with constant rate. Basically, there are four Thorthormi glacial lakes numbering 1, 2,3,4,5 as these all are located in the same vicinity but separated by some moraine dammed and there is every chance that these five glacial lakes will form one and discharge a very huge volume of water in near future. The highest rate of expansion in term of area, was Thorthormi_1 with 0.036Km^2 per year and the lowest rate was Thorthormi_4 with 0.002km^2 per year. The highest in perimeter was also Thorthormi_1 with 0.232km per year and volume too with 0.0011km^3 per year. The total glacial lake area was increasing constantly from 1990 till 2007 but it was reduced in 2009 from 3.37 km^2 to 3.49km^2. This is due to the mitigation measures taken place in early 2009 by Royal Government of Bhutan.

Therefore, overall it is seen that due to the global warming, there is an increase of temperature and also the melting of glaciers as well as expansion of glacial lakes due to the water melted from glaciers. Among the glaciers, the fastest retreating rate of glacier observed was Thorthmi glacier (T-GL) and the others are lesser than this. So it is considered to be a C-type glacier. This C-types of glacier is basically considered to be a clean glacier without mixers of debris and C-types are always considered to be a faster in melting than D-types glaciers.

The whole watershed area was taken for land classification and it is seen that there is some changes in land use classification every year. Since there is no settlement around the study area, the classes that are taken for the classification were snow/glacier, ice, forest, grassland and water bodies. The reduction rate of glacier is 1% area per year, increment rate for water bodies was 0.4 % area per year and forest with an increment of 1.2 % area per year. In this case, there is an increment of forest, the reason could be just due to the global warming with an increase of temperature in high altitude, there is a lengthening of growing seasons which supports for the plants' growth and the another reason could be due to an increase of CO_2, there is an enhancement of photosynthesis process in plants which is very helpful for the plants' growth. These two reasons are mainly supports for the forest trees to increase at higher altitude in Himalaya region.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE OF STUDY

6.1 CONCLUSION

With help of historical data of temperature and rainfall of around 15 years and with satellite maps of four different years, the study has been carried out. The digitization and computational purposes were done by using ArcGIS 9.3. On top of that land cover mapping and unsteady flow analysis of river Pochu has been done with the help of HEC-RAS software.

Based on the study the following points can be drawn.

1. The trend analysis for temperature shows that the temperature is increasing with weak significant value for the past 15 years from 1995 to 2009. The seasonal trend of the temperature slope is generally positive and monthly trend top shows some increasing trend with positive Sen's slope (Q). In case of seasonal trend, the highest slope (0.065°C) was in winter. It is noticeable that from 2001, there was abrupt rise of temperature. For monthly trend, January and December showed the biggest values of slope (Q).
2. The trend analysis on rainfall showed a general decreasing trend for the past fifteen years. It is also analyzed both seasonally and monthly basis for fifteen years. In case of seasonal, there is significant value showing decreasing trend with negative Z_{mk} value of -1.97 and for the monthly, June, July and August are showing significantly decreasing trend. In general, the rainfall is decreasing with weak value of -9.71mm.
3. The glaciers of four different years for four glaciers were analyzed and found out that the thicknesses were reducing at different rates. From 1990 to 2001, rate of decreasing was 0.08 meter per year to 0.26 meter per year and from 2001 to 2007, decreasing rate was 1.95 meter per year to 2.35 meter per year and in general, rate of decreasing was 0.99 to 1.0 meter per year from 1990 to 2009.
4. Due to climate change, there is retreat of glacier is observed in the study area. In the present study, the biggest rate of vertical retreating of the glaciers was Thorthormi (T-GL) with 35.27 meter per year and the smallest one was Bechung (B-GL) with 15.27 meter per year. In case of areal retreating of the glaciers, the biggest ones are Thorthormi (T_GL) and Luggye (L-GL) 0.2km^2 per year and smallest one is

Rapstreng (R-GL) with 0.112 km^2 per year.The change of glaciers are in percentage wise was more from 2001 to 2007 with 48 to 50 (%) rather than 1990 to 2001 with 2 to 11 (%) and from 2007 2009 with 2 to 15 (%).

5. Expansion of glacial lakes both in area and perimeter were significantly constant in all the glacial lakes. But in Drukchung glacial lake shows that the decreasing rate on a real expansion with the value of -10.14(%) from 1990 to 2001 and -7.97 from 2001 to 2007. And also Thorthormi glacial lake is showing decreasing rate (-11.15 %) from 2007 to 2009, this is due to mitigation measures taken on noticing the growth of lakes in size. The biggest overall expansion of glacial lakes in terms of area are Thorthormi and Luggye glacial lake with value of 0.036 km^2 per year and the smallest one is Bechung glacial lake with value of 00.9 km^2 per year. But Drukchung glacial lake is decreasing with the value of -0.0003km^2 per year.The biggest volume increment for glacial lake was Thorthormi and Luggye with value of 0.0011 km^3 per year and 0.0019 km^3 per year respectively.
6. Land cover mapping was done for the study area by using ERDAS imagine 2010 mainly to see the changes of glacier and water bodies within that whole watershed area. The area of glacier decreases by -4.51km^2 per year (-1.0% per year), forest area increases by 5.15 km^2 per year (1.2% per year), grass area decreases by -2.62 km^2 per year (-0.6% per year) and water bodies increases by 1.59 km^2 per year (0.4 % per year).
7. Unsteady state flow modeling of River Pochu, showed that there will be flooding at the cross-section between B and C as shown in Figure 5.31.
8. Lastly based on the study it can be concluded that there is impact of climate change on glaciers of Lunana region and as a whole of Bhutan too. With effect of climate change, there is melting of glaciers, expansion of glacial lakes and increase of volume of rivers. In nutshell, formation of potential dangerous glacial lakes which is called as Glacial Lake Outburst Flood (GLOFs) is very much prominent in Bhutan as per the scenario of global warming. And it also assumes that Thorthormi (T-GL) glacier is to be a clean glacier (C-type) as its rate of retreating is faster than other glaciers.

6.2 FUTURE SCOPE OF STUDY

With time due to the global warming, the temperature keeps on increasing and research will be more complicated with lots of factors considerations. Therefore, with physical survey on site can perform more realistic research considering with adequate data.

i) The 2D analysis on Pochu River can be performed with adequate data of cross-sections at a certain intervals of river by surveying.

ii) Dam breach analysis of glacial lakes would be performed if there are precise data on properties of glacial lake as well as properties of soil that the lake is made out of. Here the glacial lake is considered to be a similar of that of earthen dam and so it should be known the major problems which really cause of failures.

iii) Careful evaluation by detailed studies of the lakes, damming materials and surrounding conditions are essential in choosing appropriate methods for starting the mitigations.

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