# Impact of Climate Change on Himalayan Glaciers and Glacial Lakes

## Case Studies on GLOF and Associated Hazards in Nepal and Bhutan

Samjwal Ratna Bajracharya
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ICIMOD

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# Foreword

**Director General**
International Centre for Integrated Mountain Development

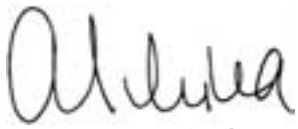
The Himalayas have the largest concentration of glaciers outside the polar region. These glaciers are a freshwater reserve; they provide the headwaters for nine major river systems in Asia – a lifeline for almost one-third of humanity. There is clear evidence that Himalayan glaciers have been melting at an unprecedented rate in recent decades; this trend causes major changes in freshwater flow regimes and is likely to have a dramatic impact on drinking water supplies, biodiversity, hydropower, industry, agriculture and others, with far-reaching implications for the people of the region and the earth's environment. One result of glacial retreat has been an increase in the number and size of glacial lakes forming at the new terminal ends behind the exposed end moraines. These in turn give rise to an increase in the potential threat of glacial lake outburst floods occurring. Such disasters often cross boundaries; the water from a lake in one country threatens the lives and properties of people in another. Regional cooperation is needed to formulate a coordinated strategy to deal effectively both with the risk of outburst floods and with water management issues.

The International Centre for Integrated Mountain Development (ICIMOD) in partnership with UNEP and the Asia Pacific Network and in close collaboration with national partner organisations documented baseline information on the Himalayan glaciers, glacial lakes, and GLOFs in an earlier study which identified some 200 potentially dangerous glacial lakes in the Himalayas. The study published here builds upon these past initiatives and investigates the impact of climate change on selected glaciers and glacial lakes.

The publication provides an account of glacier retreat and growth of glacial lakes in two selected river sub-basins, one in Nepal and one in Bhutan. It describes important methodological aspects of assessing the vulnerability for GLOF hazards based on empirical data and evidence. It also investigates the possibility of devising a method for regular temporal monitoring of glacial lakes in remote and inaccessible mountain locations using satellite-based techniques. The results provide a basis for the development of monitoring and early warning systems and planning and prioritisation of disaster mitigation efforts that could save many lives. The report also provides useful information for those concerned with water resources and environmental planning.

This report is also being packaged in a multi-media CD-ROM with films, 3-D visualisation photographs, and satellite images. The report and multimedia product will be useful for scientists, planners, and decision makers, as well as for raising the awareness of the public at large to the potential impacts of climate change in the Himalayas. With this information, we hope to contribute to improving the lives of mountain people and help safeguard future investments in the region. It highlights the need to replicate, refine, and scale up such studies, using scientific approaches and empirical evidence, in other parts of the Himalayan region. We are convinced that it will increase the awareness of the readers of the need to support initiatives.

ICIMOD is grateful to the United Nations Environment Programme Regional Office for Asia and the Pacific (UNEP/ROAP) for its support for this work. We are also pleased that the project has enabled us to continue to strengthen our collaboration with the Royal Government of Bhutan's Department of Geology and Mines and to continue to assist in developing regional capacity and co-operation. We are grateful to the European Space Agency (ESA) for providing satellite images for regular temporal monitoring of the Imja glacial lake in Nepal. Finally, I wish to thank the authors and many contributors for preparing this timely and relevant report at a time when the issue of climate change is being hotly debated in the international arena. We hope that this report will serve as a milestone for studying the impact of climate change in the Himalayas.



**Dr. Andreas Schild**
Director General
ICIMOD

# Foreword

## Executive Director
United Nations Environment Programme

Glaciers are one of the most sensitive indicators of climate as they grow and shrink in response to the changing air temperature. The glaciers of the Hindu Kush–Himalaya (HKH) are nature's renewable storehouse of fresh water from which hundreds of millions of people downstream benefit just when it is most needed during the dry hot season before the start of monsoon. Understanding the pattern of snow accumulation and melting is therefore important for the appropriate utilization of this Himalayan water resource. Observing glacier advancement and recession is also important as it can assist in identifying and thus mitigating mountain disasters in order to safeguard the livelihoods of vulnerable mountain people and their downstream neighbors.

Climate change in the Himalayas: Monitoring of Glaciers and Glacial Lakes is one of the outputs under the Bali Strategic Plan for Technology Support and Capacity Building. The Bali Strategic Plan, adopted by 23rd session of UNEP Governing Council in 2005 provides an opportunity for developing countries and countries in economic transition to coherently address the needs, priorities and responsibilities in the field of environment.

The book is built upon the research which UNEP supported during 1999 – 2001, where comprehensive inventory and a geographic information system (GIS) database of glaciers and glacial lakes in Nepal and Bhutan were prepared using available maps, satellite images, aerial photographs, reports, and field studies. This report includes a description of the methods used to identify glaciers and glacial lakes, including those that are potentially dangerous. It is complemented by an inventory and maps of the glaciers and glacial lakes in Nepal and Bhutan. The book includes a summary of the results of studies of various glacial lakes and a brief review of the causes and effects of known glacial lake outburst floods or GLOF events in Nepal and Bhutan.

I am sure that this comprehensive report and digital database will be of service to all the scientists, planners and decision-makers working in and outside the region in this field. Through informed actions, we hope it will contribute to improving the lives of those living in the mountains and help safeguard future investments, such as infrastructure for the benefit of people in the region.

UNEP is grateful to the International Centre for Integrated Mountain Development (ICIMOD) for carrying out this important project and to both national governments concerned for their

valuable support and advice. We are also pleased that this project has enabled us to continue and strengthen our collaboration in assisting to develop regional capacity with the Department of Hydrology and Meteorology (Government of Nepal) and the Department of Geology and Mines, Ministry of Trade and Industry (Royal Government of Bhutan).

**Achim Steiner**
United Nations Under-Secretary General
and Executive Director
United Nations Environment Program

# Preface

In the face of global warming, most Himalayan glaciers have been retreating at a rate that ranges from a few metres to several tens of metres per year, resulting in an increase in the number and size of glacial lakes and a concomitant increase in the threat of glacial lake outburst floods (GLOFs). Such climate changes have ultimate effects on the life and property of the mountain people living downstream. While the effect of human activity on global climate is still being hotly debated, the retreat of glaciers in the Himalaya is compelling evidence of the need for action on climate change.

Approximately 15,000 glaciers (covering an area of 33,340 sq.km), and 9000 glacial lakes throughout Bhutan, Nepal and Pakistan, as well as selected river basins in China and India were documented in a baseline study conducted earlier by ICIMOD, UNEP, and the Asia Pacific Network for Global Change Research (APN). Twenty-one GLOF events have adversely affected Nepalese territory in the recent past and to date over 200 potentially dangerous glacial lakes have been documented across the Himalayan region. These facts underline the urgent need to enhance scientific knowledge of glacier environments by continuously monitoring glaciers and glacial lakes, carrying out vulnerability assessments, implementing mitigation and adaptation mechanisms, and developing a glacial lake outburst flood (GLOF) early warning system. Regional co-operation to develop a coordinated strategy to deal with trans-boundary issues related to the impacts which can occur as a result of climate change is also required.

This publication focuses on the effects of climate change on glaciers and glacial lakes in two hotspots of glacial activity in the Himalaya: the Dudh Koshi sub-basin of Nepal and the Pho Chu sub-basin of Bhutan. Both these basins have witnessed devastating GLOF events in the recent past. The GLOFs at Dig Tsho in 1985 (Nepal) and Luggye Tso in 1994 (Bhutan) are considered 'textbook' case studies of GLOF events and have drawn the attention of researchers world-wide. A multi-media CD-ROM is being prepared as a companion to this book and will be helpful in raising awareness about the sensitivity of climate change to policy- and decision-makers, the concerned scientific community, and the general public. These materials will be helpful in designing mitigation measures to help safeguard human lives and valuable infrastructure in hazardous river valleys.

While this and other activities are helping to raise awareness of the risks posed by GLOFs, it will also be essential to replicate these studies and to continue to extend them systematically to include other high-risk areas in the Himalaya. The scientific modelling approaches and the empirical methods discussed here are both needed first steps that will be valuable in refining and scaling up this type of investigation to other Himalayan hot-spots. What is needed now is urgent action by the international community to help develop even better scientific understanding of the consequences of global climate change and to take the corrective and precautionary measures before it is too late.

Samjwal Ratna Bajracharya
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Basanta Raj Shrestha

# Acknowledgements

This book is an outcome of an ICIMOD project on 'Capacity building and early warning activities on GLOF' and a part of the Bali Strategic Plan (BSP) for Technology Support and Capacity-building adopted in Bali, Indonesia, on 4 December 2004 by the Intergovernmental Working Group. The United Nations Environment Programme (UNEP) Regional Office Asia and the Pacific also supported this project.

We are grateful to Deo Raj Gurung, Karma Toeb, and Tashi Gyalmo from the Department of Geology and Mines, Ministry of Trade and Industry of Bhutan, who were actively engaged in the project particularly in the field studies and photography in Bhutan. Thanks also go to the Director General of the Department of Geology and Mines, Dorji Wangda, for kind cooperation and support while implementing the project. We thank Pravin Raj Maskey, Ministry of Water Resources, and Sharad Prasad Joshi, Water and Energy Commission Secretariat, Government of Nepal, for their support in the GLOF modelling of the Raphstreng Tso, Bhutan, for helping to draft part of the Terrain Classification in Chapter 5, and for their fieldwork in the Khumbu region. Thanks also go to ICIMOD colleagues Arun Shrestha, Birendra Bajracharya, and Lokap Rajbhandari for GLOF modelling of Imja Tsho.

Our sincere thanks also go to the former Director General of ICIMOD, J. Gabriel Campbell, for supporting the beginning of this project and to Andreas Schild, present Director General of ICIMOD, for seeing it through to its completion.

We would also like to thank Jean Charles and Jürg Lichtenegger of the EDUSPACE Operational Team for providing the European Space Agency RADAR satellite images monthly-basis through the ENVISAT Project to ICIMOD; this data was used for the temporal monitoring of Lake Imja Tsho for 1st-stage early warning.

Thanks also go to Vishnu Dangol, Tribhuvan University, and Jürg Lichtenegger for reviewing the manuscript and making valuable comments. We are also indebted to Megh Raj Dhital (Tribhuvan University), and Richard L. Armstrong (National Snow and Ice Data Centre) for their critical review of the manuscript; and to the editors A. Beatrice Murray (ICIMOD) and Isabella C. Bassignana Khadka (consultant) for helpful insights. A heartfelt thanks to the layout persons (Dharma Ratna Maharjan and Gauri Dangol) for their hard work in preparing this manuscript in a very short time.

We would also like to thank Monica Moktan for office assistance and Bidya Banmali Pradhan for coordinating the project processes with UNEP/ROAP. Last but not least, we wish to thank Surendra Shrestha, Regional Director of UNEP/ROAP for his timely and strong support and advice while implementing the project.

# Executive Summary

The global mean temperature is expected to increase between 1.4 to 5.8ºC over the next hundred years. The consequences of this change in global climate are already being witnessed in the Himalayas where glaciers and glacial lakes are changing at alarming rates. Himalayan glaciers are retreating at rates ranging from 10 to 60m per year and many small glaciers (<0.2 sq.km) have already disappeared. Our study shows that the terminus of most of the high altitude valley glaciers in Bhutan, China, and Nepal are retreating very fast; vertical shifts as great as 100m have been recorded during the last fifty years and retreat rates of 30m per year are common. As glaciers retreat, glacial lakes grow, and many Himalayan basins are reporting very fast growing lakes. A remarkable example is Lake Imja Tsho in the Dudh Koshi sub-basin (Khumbu–Everest region); while this lake was virtually nonexistent in 1960, it now covers nearly 1 sq.km and the Imja glacier which feeds it is retreating at an unprecedented 74m per year (between 2001 and 2006). Similar observations were made in the Pho Chu basin of the Bhutan Himalaya, where the change in size of some glacial lakes has been as high as 800 per cent over the past 40 years. At present, several supraglacial ponds on the Thorthormi glacier are growing quickly and merging. These lakes pose a threat because of their proximity to other large glacial lakes in the Pho Chu sub-basin where, in a worst-case glacial lake outburst flood (GLOF) scenario, they could cascade on to these other lakes with catastrophic consequences.

The study stresses the importance of methodologies used to assess glacier retreat, the expansion of glacial lakes and the impact of GLOFs. The hydrological modelling of glacial lakes, terrain classification, and vulnerability assessment are important scientific means to understand GLOF impacts. They help in devising mitigation measures and early warning systems. A dam-breach model developed by the National Weather Services (NWS-BREACH) was used to simulate the outburst hydrographs of Lakes Imja Tsho in Nepal and Raphstreng Tso in Bhutan. The model provides information on discharge and flood arrival time in downstream areas.

Based on observations of damage caused by the Dig Tsho GLOF of 1985, the vulnerability of various terrain units in the vicinity of a possible Imja Tsho GLOF was assessed. This terrain classification scheme provided valuable information on the possible extent of the damage to be expected in the event of an Imja Tsho GLOF. The vulnerability analysis in the Imja and Dudh Koshi valleys indicated that the upper terrace of the Syomare village as well as lower terraces identified in Ghat, Chutawa, Chermading, Phakding, Benkar, Tawa, and Jorsalle villages could be severely damaged by a GLOF event at Lake Imja Tsho.

GLOF mitigation measures and early warning systems applied in the Nepal and Bhutan Himalayas are also discussed. Such techniques are quite expensive and require much detailed field-work and maintenance, an alternative, which is being considered in a feasibility study, is regular temporal monitoring of glacial lakes by RADAR satellite-based techniques to detect any changes and provide an early warning.

# Acronyms and Abbreviations

| | |
|---|---|
| C-type | clean or debris free glacier |
| Cham_gl | chamkhar Chu glacial lake |
| D-type | debris covered glacier |
| DEM | digital elevation model |
| DHM | Department of Hydrology and Meteorology |
| etm | enhanced thematic mapper |
| GLOF | glacial lake outburst flood |
| HKH | Hindu Kush-Himalayas/n |
| ICIMOD | International Centre for Integrated Mountain Development |
| IPCC | Intergovernmental Panel on Climate Change |
| Kdu_gl | Dudh Koshi glacial lake |
| Kdu_gr | Dudh Koshi glacier |
| Kuri_gl | Kuri Chu glacial lake |
| Landsat | Land Resources Satellite |
| LISS | Linear Imaging and Self-Scanning Sensor (IRS) |
| Magd_gl | Mangde Chu glacial lake |
| MCC | Meteor Communication Corporation |
| MOS | Marine Observation Satellite |
| Mo_gl | Mo Chu glacial lake |
| MSS | Multi Spectral Scanner (Landsat) |
| 'n' | Manning's roughness coefficient |
| Pho_gl | Pho Chu glacial lake |
| ppm | parts per million |
| ROAP | Regional Office Asia and the Pacific |
| UNEP | United Nations Environment Programme |
| USGS | United States Geological Survey |
| WECS | Water and Energy Commission Secretariat |
| WHO | World Health Organisation |
| WMO | World Meteorological Organisation |

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