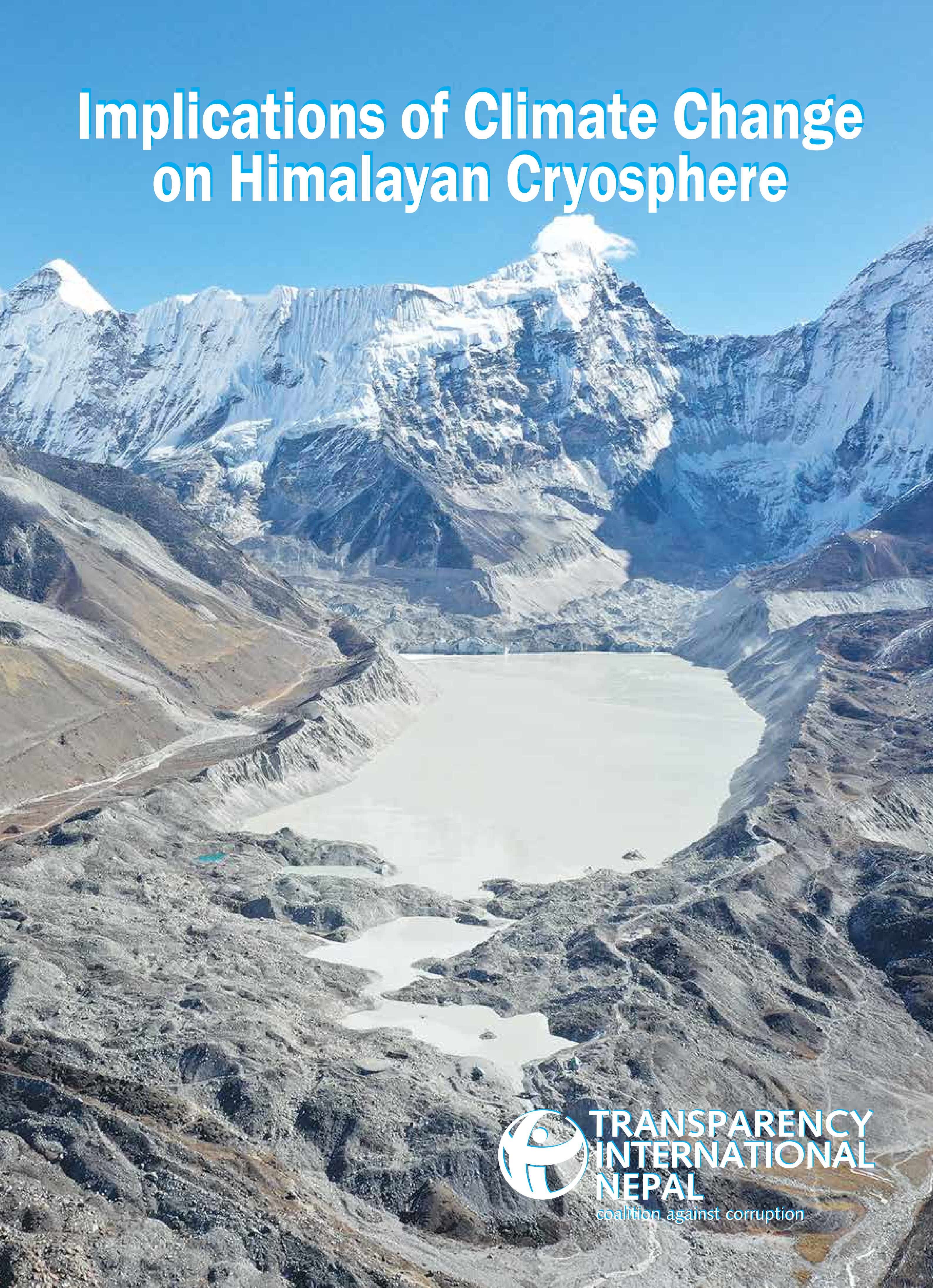
Implications of Climate Change on Himalayan Cryosphere



सारांश

द्रुत जलवायु परिवर्तनले पृथ्वीको प्राकृतिक स्वरूपमा परिवर्तन भइरहेको छ, जसले गर्दा पृथ्वीमा रहेको सबैभन्दा संवेदनशील मानिएको हिमखण्डको भण्डारहरूमा नकारात्मक असर देखा परिरहेको छ । विश्वव्यापी तापमानमा हालको समयमा भएको वृद्धि, वर्षाको ढाँचामा आएको परिवर्तन तथा अन्य मौसमी परिवर्तनले गर्दा हिमखण्डको वर्तमान स्थिति र भविष्यमा सिधा प्रभाव पर्दछ । हिमाली क्षेत्रको भौगोलिक अवस्था, उत्तर-दक्षिणमा छोटो दूरीमा उचाइ परिवर्तनको कारणले तापक्रम र वर्षाको भिन्नतामा उच्च परिवर्तन देखिएको छ । यी परिवर्तनका कारणले हिमनदी, हिउँ पर्ने क्षेत्र, हिमताल, जमिनमुनिको बरफ (पर्माफ्रोस्ट) हरूमा गम्भीर प्रभाव परिरहेको छ । नेपालको हिमाली भेगमा जमेर रहेका पानीका स्रोतहरू र यसको तल्लो तटीय क्षेत्रमा जलवायु परिवर्तनको असर बुझ्न यो अध्ययन गरिएको हो । यस प्रतिवेदनमा नेपालका हिमनदीहरू, हिमतालहरू, हिउँको आवरण, पर्माफ्रोस्ट र जलविज्ञानको अवस्था बुझ्न विभिन्न स्रोतबाट वैज्ञानिक तथ्यांकहरू संकलन गरी विस्तृत समीक्षा र विश्लेषण गरिएको छ । विभिन्न क्षेत्रीय अनुसन्धान र रिमोट सेन्सिङका अध्ययनहरूले हिमालय क्षेत्रका हिमनदीहरूको क्षेत्रफल र आयतन घट्ने क्रममा रहेको तथ्यांकहरूले देखाएको छ ।

नेपालमा सन् १९७७ देखि २०१० सम्म करिब २४ प्रतिशतले हिमनदीको क्षेत्रफल घटेको एक अध्ययनको निष्कर्ष छ । सन् १९७० देखि २००७ सम्म नेपालको खुम्बु क्षेत्रमा पर्ने इम्जा र ल्होत्से हिमनदीको उचाइ करिब -२०.६ ±२.५ मिटरसम्म घटेको अध्ययनको निष्कर्षमा पाइएको छ । यसैबीच, हिमाली क्षेत्रमा अवस्थित हिमताल र यिनीहरूको तीव्र विकासले हिमताल विस्फोटबाट हुने बाढी (ग्लोफ) को जोखिम, जलवायु परिवर्तनको अन्य असरमध्ये सम्भावित खतरनाक हुने अध्ययनको निष्कर्ष रहेको छ । हाल नेपालको तीन प्रमुख जलाधारहरू (कोशी, गण्डकी र कर्णाली) मा सम्भावित खतरनाक ४७ वटा हिमतालहरू पहिचान गरिएका छन्, जसमध्ये २१ वटा नेपालको उच्च हिमाली क्षेत्रमा, २५ वटा तिब्बत, चीनमा र एउटा भारतमा पर्दछन् । हालसम्म नेपाल हिमशृंखलाबाट ३५ वटा हिमताल विस्फोटन भएको विभिन्न स्रोतमा उल्लेख गरिएको छ । तीव्र हिमनदी पग्लिने क्रम, भूस्खलन, माटोको क्षयीकरण र कमजोर भू-बनोटका कारण पारिस्थितिक प्रणालीमा नकारात्मक प्रभावका लागि योगदान गर्दछ ।

हिमनदी, हिउँ र पर्माफ्रोस्टको बढ्दो पग्लिने क्रमले यस क्षेत्रको जलस्रोतमा फेरबदल आउने र दीर्घकालीन असरहरू पर्ने आँकलन गरिएको छ । जसको कारणले खासगरी सुक्खायाममा तल्लो तटीय क्षेत्रमा भविष्यमा पानीको उपलब्धता, जलविद्युत् उत्पादन, कृषि, खानेपानी आपूर्ति, भूमिगत पानी र अन्य उद्योगहरूमा प्रत्यक्ष असर पर्ने देखिन्छ । समग्रमा पानीको उपलब्धतामा कमी आई दुर्गम तल्लो तटीय क्षेत्रमा बसोबास गर्ने समुदायमा जोखिम बढ्ने देखिएको छ । नेपालको हिमाली क्षेत्रमा रहेका ठूला हिमशृंखलाहरू, शिखरहरू, हिमनदीहरू, हिउँले ढाकिएका सुन्दर परिदृश्यहरूका कारण लाखौं पर्यटकहरूले यो क्षेत्रको भ्रमण गर्ने र यसले देशको अर्थव्यवस्थामा महत्वपूर्ण योगदान पुऱ्याइरहेको छ । जलवायु परिवर्तनले यस्ता परिदृश्यहरूको सुन्दरतामा ह्रास आउने, अनि विपद्का घटना पनि बढ्दै गइरहेको अवस्थामा पर्यटन क्षेत्र पनि शिथिल बन्ने अनुमान गर्न सकिन्छ ।

नेपालको हिमाली क्षेत्रमा भएका अनुसन्धानहरू सीमित भए पनि उपलब्ध अनुसन्धानका स्रोतअनुसार यो क्षेत्रमा जलवायु परिवर्तनले प्रत्यक्ष तथा अप्रत्यक्षरूपमा असर पर्ने कुरा स्पष्ट देखिन्छ । यसले दीर्घकालीन असरहरू विभिन्न क्षेत्रमा पर्ने देखिन्छ । तर, यो क्षेत्रमा पर्याप्त अध्ययनहरू नभएका र सम्भावित असरको लेखाजोखा पनि पर्याप्त नभएको देखिन्छ । हिमाली भेगमा पर्याप्त संख्यामा जल, हिउँ, तथा मौसम मापन केन्द्रको स्थापना गर्नु आवश्यक देखिएको छ । विभिन्न राष्ट्रिय तथा अन्तर्राष्ट्रिय सम्मेलनहरूमा जलवायु परिवर्तन र यसले नेपालको हिमाली क्षेत्रमा पारेको प्रभावबारे आवाज उठाए पनि सम्बन्धित निकायहरूले प्रभाव न्यूनीकरण तथा अनुकूलनका कार्यक्रमहरूमा चासो नदिइएको पाएको छ ।

हरितगृह ग्यासहरूको उत्सर्जनमा नेपालको हिस्सा नगन्य मात्रामा भए पनि उत्सर्जन न्यूनीकरण गर्ने खालका कार्यक्रमहरूमा केही प्रयास भइरहेका छन् । तर पनि उच्च हिमाली भेगमा जलवायु परिवर्तनले भइरहेको असरहरू रोकथाम तथा न्यूनीकरण गर्ने खालका पर्याप्त मात्रामा कार्यक्रम र योजना सञ्चालनमा नआएको देखिएको छ । पानीको भण्डारका रूपमा रहेका उच्च हिमाली भेग तथा यसको तल्लो तटीय क्षेत्रमा भविष्यमा हुन सक्ने असर आँकलन गरी न्यूनीकरणका लागि सरकारी, गैरसरकारी, अनुसन्धानकर्ता तथा अन्य निकायहरूबाट समयमा नै कार्यक्रम सञ्चालन गर्नुपर्ने देखिन्छ । त्यसैगरी, यस क्षेत्रमा उचित व्यवस्थापन तथा भविष्यमा हुन सक्ने विपद् कम गर्नका लागि पर्याप्त नीति, लगानी र कार्यविधिको संयन्त्र तयार गरी समयमै पर्याप्त अनुसन्धानका कार्यक्रमहरू सञ्चालन गर्न जरुरी देखिन्छ ।

Implications of Climate Change on Himalayan Cryosphere

TRANSPARENCY INTERNATIONAL NEPAL
coalition against corruption

Report : **Implications of Climate Change on Himalayan Cryosphere**

Study Team : **Local Action for Global Health and Environment Training and Research Centre (LTRC) Pvt. Ltd.** **(Mohan Bahadur Chand)** **in support of Himalayan Cryosphere, Climate and Disaster Research Center (HiCCDRC), Kathmandu University, Nepal** **(Rijan Bhakta Kayastha, Rakesh Kayastha)**

Published : Kathmandu, December 2021

Publisher : Transparency International (TI) Nepal
Ghar No.: 57/62, Chhakkubakku Marga, New Baneshwor
Kathmandu, Nepal
Phone: 977-1-4475062, 4475112
Email: trans@tinepal.org
Website: www.tinepal.org
FB/Twitter: tinepal
Hotline: 1660 01 22211

Support : TRANSPARENCY INTERNATIONAL the global coalition against corruption; Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

ISBN : 978-9937-9402-5-2

FOREWORD

Transparency International (TI) Nepal, founded in 1996, is a civil society organization dedicated to increasing public accountability and curbing corruption in Nepal. It is the national chapter of the global anti-corruption movement led by Transparency International.

TI-Nepal focuses on policy advocacy, research, coalition building and public sensitization as its core areas of operation. It also implements a range of projects that aim to promote integrity and transparency. Its on-going projects focus on climate change and social accountability sectors.

Climate Governance Integrity (CGI) project works on building integrity at policy, implementation and post-implementation levels in the process of combating climate change, through interactions, observations, research, awareness programs, advocacy, sensitization and grievance redressal.

Under the CGI project, TI-Nepal initiated this study titled 'Implications of Climate Change on Himalayan Cryosphere' to review and analyze past studies on cryosphere focusing on snow, glacier, glacial lake and permafrost in Nepal and recommend necessary actions for their proper utilization and protection.

The study concludes that climate change will have adverse implications at multiple level on the Himalayan cryosphere and urges the Government, International Donors, Civil Society and the Private sector to immediately prioritize mitigating steps. In addition, more studies on himalayan cryosphere and climate change are recommended.

TI Nepal acknowledges the valuable efforts made by the study team led by Mohan Bahadur Chand (Local Action for Global Health and Environment Training and Research Center Pvt. Ltd., Dhangadhi, Kailali) with Rijan Bhakta Kayastha (Department of Environmental Science and Engineering, Kathmandu University, Dhulikhel, Kavre) and Rakesh Kayastha (Department of Environmental Science and Engineering, Kathmandu University, Dhulikhel, Kavre), as members.

TI Nepal also extends its gratitude towards the institutions and individuals for their co-operation during the course of this study and, for their constructive suggestions and support in administering the study.

Padmini Pradhananga
President
Transparency International (TI) Nepal

TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS

AVNIR	Advanced Visible and Near Infrared Radiometer
CL	Confidence Level
DGM	Glacio-hydrological Degree-Day Model
DHM	Department of Hydrology and Meteorology
DPRP	District Disaster Preparedness and Response Plan
DRRM	Disaster Risk Reduction and Management
ELA	Equilibrium Line Altitude
GDP	Gross Domestic Product
GERM	Glacier-Evolution and Runoff Model
GLOFs	Glacial Lake Outburst Floods
GloGEM	Global Glacier Evolution Model
HKH	Hindu Kush Himalayas
HMA	High Mountain Asia
m w. e. a-1	Meter Water Equivalent per Year
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
Km2	Square Kilometres
LAPA	Local Adaptation Plan of Action
LDCRP	Local Disaster and Climate Resilient Plan
m a. s. l.	Meter above Sea Level
m a-1	Meter per Year
m w. e.	Meter Water Equivalent
m	Meter
m3	Cubic Meter
NASA	National Aeronautics and Space Administration
NGS	National Geographic Society
NSH	North Side of Himalayas
oC/yr	Degree Centigrade per Year
RCP	Representative Concentration Pathways
RGI	Randolph Glacier Inventory
SSH	South Side of Himalayas
UNDP	United Nations Development Programme
Yr-1	Per YearaO

1. SUMMARY

Climate change is altering the natural function of the earth where the cryosphere (frozen water) is the most sensitive part of this and one of the main parts to face negative changes. The cryosphere consists of mountain glaciers and continental ice sheets, permafrost, seasonal snow and ice cover and sea ice. The recent increase in global temperature, changes in precipitation patterns and other climatic variables have direct implications on current and future status of the cryosphere in the world. For the implication of climate change in Himalayan cryosphere, this study carried out in the Nepal Himalaya which lies within the central region of the Hindu-Kush-Himalayan region. The Himalayan region, characterized by the rapid change in altitude in short distance in its south to north direction, facing higher increasing rate of temperatures and precipitation patterns. These changes have serious implication on cryosphere including glaciers, snow cover, glacial lakes, permafrost and other cold environment of the region in terms of retreating of glacier, decreasing glacier area, permafrost and snow cover, changing the water reserves from ice to water. The different field based and remote sensing studies indicated the decrease of glaciated regions of Nepal, where glacier area decreased by more than 24% between 1977 and 2010 in the Nepal Himalaya. Ice reserve decreased by 29% in that period. Similarly, the glaciers are lowering their elevation up to -20.6 ± 2.5 m as observed in Imja/Lhotse Shar Glacier between 1970 and 2007. A glacier inventory in 2001 recorded 3,252 glaciers with area of 5,324 km^2 but the glacier inventory of 2010 recorded 3,808 glacier with area of 3,902 km2. Similarly, glacial lakes are 1,466 in 2010 inventory with area of 64.78 km^2 area (ICIMOD, 2011) increased to 2,070 glacial lakes with its area to 85.08 km^2 (ICIMOD and UNDP, 2020). Similarly, the lower limit of permafrost shifted upward from 5,200 – 5,300 m to 5,400 – 5,500 m in the Khumbu region, Nepal between 1973 and 2004 (Fukui et al., 2006). The increased melting of snow, ice and permafrost will have direct impacts on future water availability, hydroelectricity generation, agriculture, drinking water supply and other industries by posing risks to the stability of water resources in the region. There is high potential to export the renewable energy in terms of hydroelectricity to energy deficit countries from Nepal, which can contribute significantly to the country's GDP and economy. Meanwhile, the formation and development of numerous glacial lakes in the high elevation pose risk of Glacial Lake Outburst Floods (GLOFs), as several of them are potentially dangerous. Currently, there are 47 glacial lakes that are identified as potentially dangerous glacial lakes in three major river basins of Nepal and potential to affect the Nepalese territory if they burst, while 21 are located only in Nepal. The rapid glacier melt contributes to flash floods, landslides, soil erosion, and impacts on ecosystem of the fragile mountain region. More than 35 GLOFs have been documented in different literature in Nepal Himalayas and several GLOFs assumed to occur in different part of the country, which are not documented due to remoteness and some of them are small in size. The frequency of GLOFs is increasing in recent years. Increase in melt water maybe useful for production of electricity and contribution to GDP as a positive implication in the short term, while increasing the chances of disasters can damage the hydropower and other infrastructures facilities in the downstream regions. In the long term, less water will be available for hydropower generation, irrigation, drinking water and to recharge groundwater mainly during dry periods. This will exacerbate water shortage and affect the livelihoods of rural mountain communities and many downstream regions. Mountain tourism is an important economic industry of Nepal, which attract tens of thousands tourists in mountains to observe the mountain landscape covered with snow, glaciers and beautiful peaks. The decreasing snow and glacier cover area and risk of potential cryospheric disasters can stop or reduce the tourists travelling to mountain regions which may adversely affects the larger tourism industry. Thus, the importance of cryosphere in the national development is very high and proper study of glaciers, glacial

lakes and permafrost should be carried out by expanding adequate number of hydro-meteorological stations and other measurements in higher altitudes. Also, it is very urgent to decrease water levels of potentially dangerous glacial lakes and install snow and weather monitoring stations at high altitudes.

2. INTRODUCTION

The cryosphere is an all-encompassing term for those portions of the Earth's surface where water is in solid form, including sea ice, lake ice, river ice, snow cover, glaciers, ice caps, ice sheets, and frozen ground or permafrost. A glacier is a moving body of snow and ice that has been formed through the recrystallization of snow. There are 3,808 glaciers in Nepal (ICIMOD, 2011). There are mainly two types of glacial lakes called moraine dammed and ice dammed glacial lakes. In Nepal, most of the glacial lakes are moraine dammed. There are 2,070 glacial lakes in Nepal (ICIMOD and UNDP, 2020). A moraine is an aggregate of earth materials such as soil, sand, rock etc., which are deposited chiefly by the moving glacier. A permanently frozen ground is called a permafrost if its temperature remains below 0^{o} C for two consecutive years. The permafrost in Nepal lies at an altitude of more than 5,000 m above sea level (a. s. l.) from the east to west Nepal.

The Himalayas is largely alpine, but varies dramatically with elevations, from snow-capped in higher elevations to tropical and sub-tropical climate at lower elevations, hence has a diverse vegetation. It is sensitive to climate change and variability, plays an important role in climate patterns (Shrestha and Aryal, 2011), biological and cultural diversity, water resources and its cycle. The whole Himalayan region is the source of the nine largest rivers in Asia (Jianchu et al., 2007; Williams, 2013), while central Himalaya lies in Nepal, which is the source of Ganges River. The main tributaries of the Ganges River from Nepal are Koshi, Narayani, Karnali and Mahakali. More than 800 million people live in the catchments of the Indus, Ganges, and Brahmaputra rivers and rely to varying extents on the water released from glaciers that constitute the most extensive glacier cover outside the Alaska and the Arctic.

Climate-induced cryospheric changes such as glacier retreat and decrease in snow cover extent can largely influence the timing, magnitude and distribution of seasonal discharge in the river system of Nepal Himalaya (Immerzeel et al., 2013; Kayastha et al., 2019; Kayastha and Kayastha, 2020; Lutz et al., 2014). The snow, ice, and permafrost- is an important part of the water supply in Nepal and have large economic importance especially on hydropower generation, irrigation, and drinking water supply. The hydropower generation may become one of the main contributors of the Nepal's GDP by exporting to other countries. The impact of climate change on hydroelectricity generation capacity will have a direct impact on the country's economy with change in water availability and potential climate induced disasters. Most Himalayan glaciers are losing mass at rates similar to glaciers elsewhere, except for emerging indications of stability or mass gain in the Karakoram (Bolch et al., 2012). Observed and projected changes in the cryosphere will affect the timing and magnitude of stream flows across the region, with proportionally greater impacts upstream (Bolch et al., 2019a). Past studies indicated that glaciers in this region have been retreating since the mid-19th century with some exception. The seasonal variability in river discharge can significantly affect the hydropower generation and ecosystem services in the catchment area (Shrestha et al., 2014).

Cryospheric regime has been experiencing considerable changes since the last few decades and those changes are mainly associated with increasing temperature (Bolch et al., 2019a; Radi et al., 2013; Shea et al., 2015; Xu et al., 2009). According to (Yao et al., 2012), temperature in the higher elevations of Nepal has been increasing faster than the lower elevations and global average, and this warming is highest between 4,800 and 6,200 m a. s. l. This elevation range comprises the ablation (melting) altitude of almost all glaciers in the region. The regional equilibrium line altitudes (ELAs) or the area/zone where the net mass balance (loss or gain of ice mass) is zero is shifting upwards with rising temperatures, resulting in the disappearance of debris-free lower elevation glaciers (Bolch et al., 2019b; MATTSON and E., 1993). Along with challenges associated with water availability and distribution, cryospheric changes can cause potential geo-hazards such as GLOFs, landslides, debris flow and floods, which can largely affect hydropower projects in the watershed (Bajracharya et al., 2014; Ma et al., 2010; Shangguan et al., 2014). The possible changes in river discharge will also affect the water availability from glacierized river basins. Therefore, this study is to review all available literature in the field of climate change and its impacts on Himalayan cryosphere to understand the implications of climate change in different components of the cryosphere.

3. OBJECTIVES

The importance of cryosphere is increasing day by day in the present context of the climate change. Its importance is magnified due to its strong links with water resources, hydropower, tourism, socio-economy of people living in the mountains and the Himalayas. Therefore, the main objectives of this report is to review and analyze all past studies on cryosphere focusing on snow, glacier, glacial lake and permafrost in Nepal and recommend necessary actions to be taken on cryosphere sector for its proper utilization, reduction and mitigating dangers of glacial hazards in Nepal.

4. GLOBAL AND REGIONAL CLIMATE

After the industrial revolution, human activities have warmed the atmosphere, ocean and land, producing widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere. Warming has occurred in the Himalayas, the Swiss Alps, and the central Andes and has increased with altitude (IPCC, 2021). Such elevation-dependent warming could lead to faster changes in snowline, the ELA and snow/rain transition height with high confidence. According to the IPCC report, the freezing level height in mountain areas is projected to rise and will alter snow and conditions including earlier onset of spring snowmelt and increased melting of glaciers. It is also projected that extreme precipitation will increase in major mountainous regions, with potential cascading consequences of floods, landslides and GLOFs in all climate change scenarios. Similarly, the report also showed that observed mean surface temperature increase has clearly emerged out of the range of internal variability compared to 1850-1900 in Asian region. Heat extremes have increased while cold extremes have decreased, and these trends will continue over the coming decades with high confidence. The IPCC report also reported the weakening of South and Southeast Asian monsoon with high confidence in the second half of the 20th century due to anthropogenic aerosol forcing and will be dominated by the effects of internal variability.

In order to understand the regional climate trend over Nepal, the Department of Hydrology and Meteorology (DHM), Government of Nepal analysed the temperature and precipitation data from 1971 to 2014 of different climate stations of Nepal. DHM (2017) states that annual and seasonal maximum temperatures in Nepal are showing significant upward trends. Analysis shows that minimum temperature is substantially in increasing trend only during the monsoon season in Nepal. In any season, there is no discernible trend in precipitation. Annual maximum temperature trend is significantly positive (0.056 ^{o}C/yr) in Nepal. Nepal annual minimum temperature trend is also positive (0.002 ^{o}C/yr) but it is insignificant. Pre-monsoon and monsoon precipitation patterns are only significant in a few districts, but winter and post-monsoon precipitation trends are insignificant in the majority of districts. During the monsoon season, Syangja and Parbat districts have the most significant precipitation trend. In the High Himalayan region, only pre-monsoon precipitation has a significant negative trend. Precipitation trends in other seasons are insignificant in all physiographic areas. Both at district and physiographic level, three coherent but insignificant patterns are observed. In three seasons (winter, pre-monsoon, and monsoon), there was an insignificant positive precipitation trend in the southern districts of the Far Western Region. Monsoon precipitation has decreased insignificantly in the majority of regions east of 84oE longitude. In the High Mountains, there is an insignificant highest decreasing rainfall trend in all seasons, while in the Terai, there is an insignificant maximum positive rainfall trend in all seasons, except post-monsoon. These consistent but moderate trends might be linked to short-term variations in atmospheric events.

In all seasons, except in the majority of the Terai districts in winter, the positive maximum temperature trend is extremely significant in the majority of districts (more than 90% of districts) and in all physiographic areas. It also revealed a greater warming rate of 0.086° C/year in the Higher Himalaya over that period (DHM 2017). Except for the Terai in winter and pre-monsoon, and the Siwaliks in winter, all five physiographic areas show a significant positive trend in all seasons. The highest positive trend was observed in the High Mountains and High Himalayas during the winter season, whereas the highest positive trend is observed in the Terai, Siwaliks, and Middle Mountains during the monsoon season. Seasonal and annual maximum temperature trends in relationship to altitude show a different pattern at both the district and physiographic levels, with a negative or moderate positive trend in lower altitude districts/regions and a greater positive trend in higher altitude districts/regions. During the monsoon, Dolpa district has the positive significant trend (0.046° C/yr) while Humla district has the considerably highest negative trend (-0.076° C/yr) at the district level.

In case of precipitation, rainy days are becoming more common, especially in the northern areas. Especially in the northern areas, very rainy days and extremely wet days are on the decline. Consecutive dry days are decreasing in the northwestern districts of the mid-western, while consecutive wet days are increasing in the northern districts of the mid-western, as well as the central part of western and eastern region.

Similarly, warm days and nights are becoming increasingly common in the majority of regions. In the majority of areas, the duration of warm periods is increasing. Cool days are decreasing in most districts, whereas cool nights are increasing in a few northwestern and northern districts and significantly decreasing in a few southern districts. Only in the far-western is the length of winter rising considerably. The seasonal and annual climatic trend averaged for Nepal is shown in Table 1. Similarly, seasonal and annual precipitation trends in physiographic regions of Nepal is shown in Table 2.

Table 1. Observed climatic trends of Nepal (DHM, 2017).

Seasons	Precipitation (mm/yr)		Maximum Temperature (^{0}C/yr)		Minimum Temperature (^{0}C/yr)	
	a	Q	a	Q	a	Q
Winter	0	-0.072	***	0.054	0	-0.009
Pre-monsoon	0	-0.081	***	0.051	0	-0.003
Monsoon	0	-0.085	***	0.058	*	0.014
Post-monsoon	0	-0.324	***	0.056	0	-0.005
Annual	0	-1.333	***	0.056	0	0.002

Note: Significance (a): *95% CL, **99% CL & ***99.9% CL; insignificant at 95% CL : + , 0

This shows that except for a decrease in precipitation during the pre-monsoon season, the climate in Nepal will become much warmer and wetter in the future and more pronounced in the higher Himalayan region. Climate extremes indices based on temperature and precipitation are estimated to be of more extreme occurrences in the future. Different sectors, such as water, energy, biodiversity, agriculture, and livelihoods, would be severely impacted by these changes.

Table 2. Climatic trends in different physiographic regions of Nepal

Physiographic Regions	Water		Pre-monsoon		Monsoon		Post-monsoon		Annual	
	a	Trend (mm/yr)	a	Trend (mm/yr)	a	Trend (mm/yr)	a	Trend (mm/yr)	a	Trend (mm/yr)
Tarai	0	0.09	+	1.24	0	0.51	0	-0.26	0	0.49
Siwaliks	0	0.08	0	0.75	0	-0.60	0	-0.38	0	-1.48
Mid Mountain	0	0.03	0	0.03	0	-0.45	0	-0.43	0	-1.58
High Mountains	0	-0.06	0	-0.82	0	-0.19	0	-0.50	+	-3.17
High Himalayas	0	-0.03	*	-0.74	0	-0.21	0	-0.32	+	-1.46

Note: Significance (a): *95% CL, ** 99% CL & * 99.9% CL; insignificant at 95% CL : +, 0**

5. CHARACTERISTICS AND STATUS OF HIMALAYAN GLACIERS

Glacier provides meltwater in regular basins and a reliable source of water for the downstream communities of the glacierized basin. There are more than 54,000 glaciers in the Hindu Kush Himalaya (HKH) covering a total area of 60,000 km^2 (Bajracharya and Shrestha, 2011). Out of total glaciers in the HKH region, 3,808 glaciers with a total area of 3,902 km^2 are found in the Nepal Himalaya (Bajracharya et al., 2014). The distribution of glaciers in Nepal Himalaya is presented in Figure 1.

About 89% of the glacier area is clean and 11.4% of the total glacier area covered by the debris (glacier ice covered with sand, clay, rocks and boulders). Similarly, more than 80.8% of the glaciers have size <1 km^2 and only about 19.2% of the glaciers have size >1 km^2, while 1.6% (n=62) of the glaciers with size >10 km^2. Glaciers in Nepal are distributed from 3,753 m a. s. l. to 8,401 m a. s. l. According to Bajracharya et al. (2014), the Ngozompa Glacier (Figure 2) is the largest glacier of Nepal located in the Dudh Koshi basin in the eastern Nepal Himalaya.

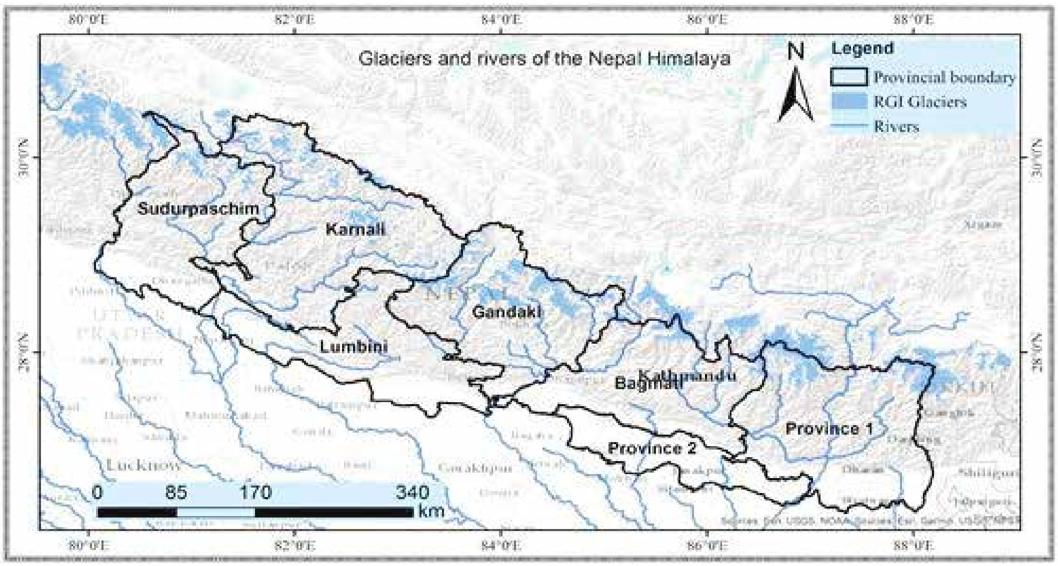


Figure 1. Glaciers and Rivers of Nepal Himalaya (Glacier data source: RGI).

The major river basins of Nepal are Koshi, Gandaki, Karnali and Mahakali basins. The Gandaki basin had the highest number and area of glaciers followed by the Koshi, Karnali and Mahakali basin respectively. There are 19 glacierized river basins in Nepal where glaciers are found (Figure 3).

Figure 2. Ngozompa Glacier in the Dudh Koshi subbasin in eastern Nepal
(Photo: Mohan B. Chand, 2018).

The distribution of glacier area in each basins is presented in Table 3. The glacierized sub-basins of Nepal area Mahakali, West Seti, Humla Karnali, Kawari, Tila, Mugu Karnali, Bheri, Kali Gandaki, Seti, Marsyangdi, Budi Gandaki, Trishuli, Indrawati, Sunkoshi, Tamakoshi, Likhu, Dudh Koshi, Arun and Tamor. Out of 19 glacierized sub-basins, Kali Gandaki had the largest area and number of glaciers while Indrawati had the smallest area of the glaciers.

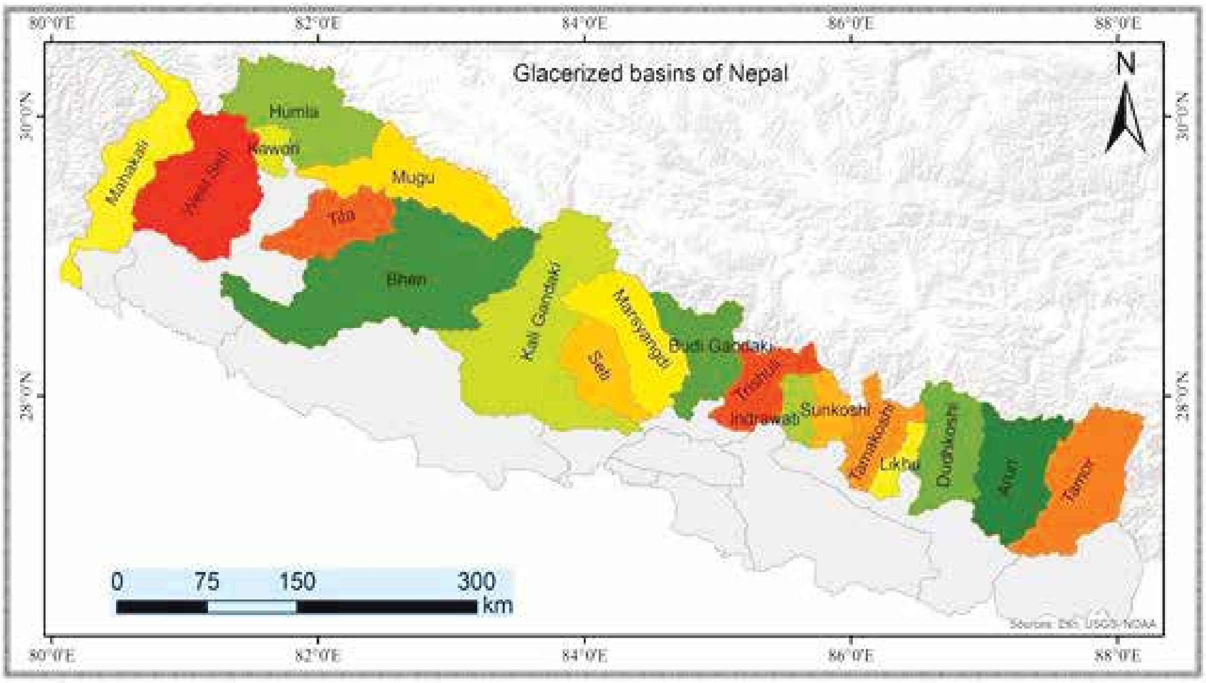


Figure 3. Nineteen glacierized sub-river basins of Nepal.

Table 3 Distribution of glacier area in sub-basins of Nepal. *(Source: Bajracharya, 2014)*				
SN	Basins	Subbasins	Basin area (km²)	Glaciated area (km²)
1	Koshi	Tamor	6,056	385.9
2		Arun	5,156	149.2
3		Dudhkoshi	4,065	391.1
4		Likhu	1,051	23.0
5		Tamakoshi	2,716	84.4
6		Sunkoshi	1,437	52.6
7		Indrawati	1,229	16.4
8	Narayani	Trisuli	2,912	207.6
9		Budi Gandaki	3,642	348.9
10		Marsyangdi	4,787	509.0
11		Seti	2,947	71.6
12		Kali Gandaki	11,862	527.4
13	Karnali	Bheri	13,575	363.8
14		Tila	3,329	26.8
15		Mugu	5,329	119.2
16		Humla	5,983	337.9
17		Kaweri	822	29.2
18		West Seti	7,378	146.0
19	Mahakali	Mahakali	5,380	112.5

All the glaciers of Nepal Himalaya experience maximum accumulation (addition of snow mass) in the monsoon season "Summer-accumulation type" due to high precipitation during this season. The western part of Nepal Himalaya also received winter precipitation as a result of westerly, however, relatively small in comparison to summer (monsoon) precipitation. The snow avalanche also causes considerable accumulation due to very steep and rugged terrain above the glaciers. The Himalayan glaciers are characterized by the presence of debris in their lower ablation zones and the thickness of debris varies from a few centimetres to meters (Benn et al., 2012; Chand et al., 2015; Chand and Kayastha, 2018; Fujii and Higuchi, 1977; Mattson and E., 1993; Östrem, 1959). The source of debris for these glaciers is due to the presence of large valleys and steep headwalls (Kraaijenbrink et al., 2017), which alter the surface energy balance and work as a barrier between the atmosphere and ice (Nicholson and Benn, 2013). The melt rate of the clean ice and debris-covered ice is different due to the difference in interaction between atmosphere and ice. Additionally, in the debris-covered glaciers, melt rate is determined by the debris thickness, thermal conductivity, moisture, porosity, albedo, and surface roughness of the debris (Juen et al., 2013; Rounce and McKinney, 2014).

6. CHANGES IN HIMALAYAN GLACIERS

Study of glaciers and their changes in Nepal Himalaya is scarce. Glacier area change studies are available mostly at basin scale and individual glacier except some regional studies. The IPCC report stated that glaciers have thinned, retreated, and lost mass since the 1970s with high confidence and their mass will likely decline with greater mass loss in higher greenhouse gas emissions scenarios in the High Mountain Asia (HMA) region, especially in Himalayas. Majority of Himalayan glaciers are retreating since the mid-19th century and changes in heterogeneity in different regions and glacier to glacier (Azam et al., 2018). Glaciers are critical to economies and livelihoods, however, volume and area of the glaciers is decreasing both in the Himalayas and globally. Field measurement, satellite observation and modelling based studies shows that, Himalayan glaciers displayed relatively large mass loss compared to other regions of HMA, with some spatial variability (Shean et al., 2020). Glaciological measurement in Nepal Himalaya has been initiated by Japanese researchers since the 1970s in the Hidden Valley, Shorong Himal and Langtang Valley (Ageta and Higuchi, 1984; Fujii et al., 1976; Fujita et al., 1997). Similarly, mass-balance studies were done in the Mera Glacier, Hinku Valley; Pokalde and West Changri Nup glaciers, Khumbu Valley in 2007, 2009, and 2010, respectively by Wagnon et al. (2013). Hindu-Kush Himalaya Cryosphere Monitoring project was initiated in Nepal by International Centre for Integrated Mountain Development (ICIMOD) and its partners; the Kathmandu University, Department of Hydrology and Meteorology of the Government of Nepal and Tribhuvan University in 2011 to monitor the mass-balances of Yala and Rikha Samba glaciers (Stumm et al., 2021).

It is estimated that the total glacier area decreased by 24% between 1977 and 2010, and the estimated ice reserves by 29% in Nepal Himalaya (Bajracharya et al., 2014). Acharya and Kayastha (2019) calculated a cumulative mass loss of -4.88 m w. e. and -0.81 $\pm$ 0.27 m w. e. a^{-1} for the 2011–2017 period using in situ measurements. Similarly, Shean and others (2020) reported a mass loss of –0.78 $\pm$ 0.13 m w. e. a^{-1} for the 2000–2018 period from remote-sensing observations. A recent study of mass balances found that directly (glaciological method) measured average annual mass-balances rates of Yala and Rikha Samba glaciers are -0.80 $\pm$ 0.28 and -0.39 $\pm$ 0.32 m w. e. a^{-1}, respectively, from 2011 to 2017 (Stumm et al., 2021). The study team also estimated the retreat of 346 m (-8.2 m a^{-1}) for Yala Glacier from 1974 to 2016 and 431 m (-18 m a^{-1}) for Rikha Samba Glacier from 1989 to 2013. Azam et al. (2018) found the similar range of mean mass balance as global average up to the year 2000, but likely negative after 2000.

A study on ten glaciers in the Everest region using the Corona spy imagery, aerial images and cartosat-1 images found significant loss of mass (-0.32 $\pm$ 0.08 m w. e. a^{-1}) since at least 1970, despite the thick debris cover (Bolch et al., 2011). They also estimated the average elevation difference of -13.3 $\pm$ 2.5 m with maximum up to -20.6 $\pm$ 2.5 m on Imja/Lhotse Shar Glacier between 1970 and 2007. This shows that, average surface lowering rate is 0.36 $\pm$ 0.07 m a^{-1}. Out of ten glaciers, most of them show maximum lowering in their mid-ablation zones, with a negligible change near their terminus. Similarly, the volume loss estimation of the ablation area of Khumbu Glacier for different time periods shows that maximum downwasting rate (-0.79 $\pm$ 0.52 m a^{-1}) is observed in the latest study period (2002-2007). The specific mass balance of all ten glaciers doubled during 2002 and 2007 compared to 1970-2007 and the greatest amount of mass loss occurred on Imja Glacier, which can be partly contributed by the calving activity in the Imja Lake and the presence of relatively thin debris-cover on the glacier.

Another study in the Everest region found consistent acceleration of glacier mass loss between the 1960s (-0.23 $\pm$ 0.12 m w. e. a^{-1}) and the modern era (-0.38 $\pm$ 0.11 m w. e. a^{-1}) from 2009 to 2018 (King et al., 2020). This study found the thinning of the glaciers around Mt. Everest by more than 100 m since the 1960s and mass loss varied depending on terminus type and surface characteristics of the glacier. The mean rate of elevation change between 1962 and 1969 was -0.28 $\pm$ 0.15 m a^{-1}, increase to mean of -0.41 $\pm$ 0.18 m a^{-1} between 1984 and 2000 and from 2009 to 2018 the mean rate was -0.52 $\pm$ 0.15 m a^{-1}. The greatest ice losses have occurred on the Barun Glacier, Lhotse Shar and Imja Glaciers. The Barun Glacier thinned by 150 m between 1962 and 2018 in its central ablation zone, while maximum thinning rate (-2.12 $\pm$ 0.09 m a^{-1}) occurred over the termini of lake-terminating glaciers between 2009 and 2018.

According to Bhattacharya et al. (2021), the Langtang region showed a negative mass balance -0.32 $\pm$ 0.07 m w. e. a^{-1} from 1964 to 2020, where rate of mass loss is found least (-0.20 $\pm$ 0.09 m w e. a^{-1}) during the earlier period (1964-1974) and highest (0.59 $\pm$ 0.14 m w. e. a^{-1}) during the latest period (2017-2019) of the study, indicates the consistent increase in mass loss rates throughout the observation period.

A study in the Koshi Transboundary River basin by Shangguan et al. (2014) found that glacier reduction was slightly faster on the south side of Himalayas (SSH, Nepal side) than the north side of Himalaya (NSH, China side). Glacier area on SSH decreased at a rate of -6.2 ± 3.2% (0.68 ± 0.36% a^{-1}), faster than on NSH during 2000 and 2009. Overall, glacier area shrunk by 321.3 ± 88.8 km^2 from 1976 to 2009 on the SSH. The variation in glaciers is heterogeneous in the studied regions of the Nepal Himalaya, as response to climate change which is contributed by different characteristics of the glaciers, i.e., size, slope, aspect, glacier type, presence/absence of glacial lakes and others.

A very negative impacts of disappearance of glaciers and less snow in Nepal has first seen in the Mustang district where a mountain village had to move due to the scarcity of drinking water. A Dhye village in the upper Mustang had moved to nearby village called Thangchung. Dhye residents are the first climate refugees in Nepal.

The above scientific data reveals that the glacier area and volume is decreasing at an alarming rate which will further impact on the water resources. Most of the glaciological studies are concentrated in the eastern and central region of Nepal Himalaya. The heterogeneity in climatic pattern and topographical variation along the Himalayas from east to west could respond differently. Lack of glacier research in the western region of Nepal Himalaya still has data gaps from this region.

7. CHANGES IN SNOW COVER

Snow cover is an important component of the cryosphere; and snowfall intensity and patterns are important for the accumulation on the glaciers. Snow cover is highly variable in contrast to glaciers, and its variation is directly proportional to intensity of precipitation, its patterns and trends. Snow cover has reduced since the early 21st century in the HMA, especially in the Himalayas (IPCC, 2021). According to IPCC, snow-covered areas and snow volumes will decrease and snow elevations will rise with high confidence. A study done by Maskey et al. (2011) showed the snow cover in February and March is higher in 3,000-4,000 m elevation zone than in the 4,000-5,000 m and 5,000-6,000 zones, while for the rest of the year in these three elevations zones, the snow cover extent is monotonously increasing with increasing elevation. At higher elevation >7,000 m elevation zone, snow cover during summer is higher than in winter. The analysis of nine years of data found that the decreasing trends of snow cover in January and in winter and increasing trends in March and autumn. They predicted the significant changes in the river flows and water resources in the region, especially in spring and would have implications for aquatic ecosystems, irrigation dependent agriculture land.

The decreasing patterns in snow cover recorded in January and increasing trends in November can be linked to increasing temperatures in December and January and decreasing temperatures in November, respectively. Availability of remote sensing data has a potential to analyse the snow cover area variability in regional extent. The snow depth and snow water equivalent are the foremost important to understand the snow characteristics and its dynamics. The seasonal and annual variability on the snow cover and its depth is immensely important to assess the water resource availability and river flow regimes. Still there is a lack of ground based snow monitoring stations over the high Himalayas and it is important to establish the network of snow monitoring stations in all the nineteen glaciated river basins of Nepal Himalaya to understand the regional snow dynamics including other climatic variables. It is predicted that significant changes in the river flows and water resources in the region, especially in spring and would have implications for aquatic ecosystems and for irrigation dependent agriculture land.

8. CHANGES IN PERMAFROST

Recent studies have described mountain permafrost degradation due to global warming in many mountain regions, including the Nepal Himalaya region. Permafrost is an important part of the cryosphere, which includes type of ground, a mixture of poorly sorted angular-rock debris and ice that has been frozen continuously for a minimum of two years and more. Thawing of permafrost can have widespread impacts in terms of environment, society, geomorphology in terms of ground subsidence, slope instability, changes in surface and subsurface hydrological regime. Permafrost form key hydrological stores in and are expected to form a larger component of base flow to rivers under climate warming scenarios. There exists is only a little information regarding the permafrost distribution and its changes in Nepal Himalayas. A study by Fukui et al. (2006) showed that the lower limit of the permafrost shifted from around 5,200 m – 5,300 m to 5,400 -5,500 m in between 1973 to 2004 in the Khumbu region of Nepal. A similar study done by Jones et al. (2018) in Nepal Himalayas estimated over 6,000 rock glaciers corresponding to 1,371 km^2 in between 3,225 and 5,675 m a. s. l. The study showed that 68% of the rock glaciers containing ice and the rock glaciers in Nepal store between 16.72 and 25.08 billion m^3 of water. In the Kanchenjunga region, the lowest altitude of active rock glacier is 4,250 m a. s. l., however, existence of permafrost was not confirmed at this altitude (Ishikawa et al., 2001).

9. GLACIAL LAKE DEVELOPMENT

Climate change has a strong impact on glaciated areas (Chevallier et al., 2011; Haeberli et al., 2013; ICIMOD, 2011; IPCC, 2007; Shi-jin and Lan-yue, 2019; Shrestha and Aryal, 2011; Xu et al., 2009) as a result, they are retreating in most regions of the world. The study on Himalayan glaciers has considerably advanced in the last decade, and the spatiotemporal frequency and amplitude of changes in Himalayan glacial lakes has been recorded as well (Haritashya et al., 2018). The climate change might lead to an increase in the size and quantity of supraglacial and proglacial lakes that combine behind the loose moraine to produce larger glacier lakes (IPCC, 2012; Worni et al., 2014). This glacier melt water accumulations have the potential to cause unstable moraine dams to burst. The Nyainqentanghla regions exhibited a decline in glacier-fed lake area, whereas the central and eastern Himalaya showed complete increases in glacier-fed lake area (Zhang et al., 2015). Glacial lakes have been categorized as critical or potentially dangerous due to rapid lake growth, glacier and moraine conditions, and mass movements into the lake (Fujita et al., 2013; ICIMOD, 2011; Ives et al., 2010; Rounce et al., 2016; Wester et al., 2019).

Another study by ICIMOD (2011) prepared a glacial lake inventory of Nepal using area threshold of >0.001 km^2 and identified a total of 1,466 glacial lakes covering an area of 64.78 km^2 and mean area of 0.044 km^2. They classified glacial lakes as moraine-dammed (66.6%), ice-dammed or supraglacial (7.3%) and glacier erosion lakes (25.1%). The highest number (346) of the lakes are found in the Humla Karnali subbasin, however the highest area (13.2 km^2) covered by the lakes are observed in the Dudh Koshi subbasin. The study also identified the 21 potentially dangerous lakes by evaluating 49 lakes with size >0.02 km^2 based on size, expansion rate, water level, dam condition, glacier characteristics, physical conditions of surroundings and intermittent activity of supraglacial lakes.

Similarly, Bajracharya et al. (2020) mapped the glacial lakes above 3,000 m a. s. l. of the Koshi, Gandaki, and Karnali trans-boundary basins of Nepal with size >0.002 km^2 for the year 2015. These basins comprises the part of the Tibet Autonomous Region (TAR) of China and India in the upstream. In total, 3,624 glacial lakes were mapped, of which 2,070 lakes lies in Nepal only with an area of 85.08 km^2 and 1,554 lakes in TAR and India. Out of total lakes mapped, 1,410 lakes have size ≥0.02 km^2 and are potential to hold significant volume of melt water and considered large enough to cause GLOFs.

Rounce et al. (2017) identified the 131 glacial lakes in the Nepal Himalaya that are greater than 0.1 km^2 and classified 11 lakes as very high risk and 31 as high risk based on mass entering the lake, the moraine stability and lake expansion. They also classified 6 lakes as supraglacial lakes, 64 as unconnected glacier fed lakes, 37 proglacial lakes and 24 non-glacier fed lakes. Slightly different number of glacial lakes are identified by Khadka et al. (2018) using the area threshold of ≥0.0036 km^2 and using the Landsat images of 2017 who revealed the 1,541 glacial lakes with total glacial lake area of 80.95 ± 15.25 km^2 in the Nepal Himalaya. They identified 1,064 (64.69 km^2) lakes as glacial-fed lakes, and the remaining 477 (16.26 km^2) as non-glacier-fed lakes. They further classified the lakes into supraglacial lakes, proglacial lakes and unconnected glacier-fed lakes. Maximum lake area was recorded in the Koshi River basin among the four major river basins of Nepal, which was largely contributed by the proglacial lakes. The number of supraglacial lakes is also highest in the Koshi River basin. They also presented the decadal expansion of glacial lakes for whole Nepal, where glacial lake area was expanded at rates of 1.63% yr^{-1} between 1977 and 1987, 0.67% yr^{-1} between 1987 and 1997, 0.77% yr^{-1} between 1997 and 2007, and 0.91% yr^{-1} between 2007 and 2017.

Similarly, in the Koshi trans-boundary basin that includes TAR, China and Nepal, 2,168 glacial lakes covering an area of 127.61 km^2 were mapped using 30 m Landsat images in the year 2010 (Shrestha et al., 2017). They classified the glacial lakes into bedrock dammed (34.8%), ice-dammed (17.7%), and moraine-dammed (47%). They found overall growth of lake area by 86.9% from 94.44 km^2 in 1977 to 127.61 km^2. The large size lakes (>0.1 km^2) expanded rapidly from a total area of 42.92 km^2 in 1977 to 63.28 km^2 in 2010 and mean growth rate was higher in Nepalese part than in the Tibetan part of the basin. Study of glacial lakes in the Everest region by Salerno et al. (2012) found 624 (7.43 km^2) glacial lakes using Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) satellite image of 10 m spatial resolution and from year 2008. Of these lakes, the unconnected glacial lakes were 170 (4.28 km^2), proglacial lakes 17 (1.76 km^2) and supraglacial lakes 437 (1.39 km^2).

A recent study by Chand (2020) in the Everest region by using very high-resolution (2-m) satellite images found 3,290 glacial lakes covering an area of 8.11 ± 0.45 km^2 using an area threshold of 20 m^2. Out of total lakes mapped, 91% were supraglacial, 0.5% proglacial and 8% unconnected glacial lakes and covering an area of 26%, 29%, 45% of total area, respectively. Although supraglacial lakes are dynamics and seasonal due to dynamics of glaciers and their morphology, however, the number of supraglacial lakes at the surface of the glaciers are expanding in recent periods and some of them are transforming to large proglacial lakes at the terminus of the glaciers (Chand and Watanabe, 2019). The persistence of these lakes is higher than the earlier period, indicating that the topology of the glaciers is also responding to recent climate change in the region. Similarly, 373 glacial lakes of total area 6.18 ± 0.75 km^2 were mapped in 2018 using Sentinel-2 images of 10 m spatial resolution in the Kangchenjunga region of the Tamor basin (Chand, 2020). This study revealed an increase in the number of glacial lakes by 406% and in area by 230% from 1964 to 2018. This rapid increase in number is caused by the formation of new supraglacial lakes and increase in area is caused by the expansion of already developed proglacial lakes. Gardelle et al. (2011) also reported the increase in area by 20% between 1990 and 2009 in the extended Everest region, Nepal.

Continuous high-frequency monitoring of glacial lake dynamics is critical for understanding their distribution, evolution, and the driving mechanism of fast expansions. The interdisciplinary approach using the multi-temporal data needs to be analysed the GLOF hazards. Remote sensing as well as regular field based monitoring of glacial lakes should be carried out to assess and identify the changes. Each topographical details such as slope of moraine dam, geophysical properties and stability of moraines, volume of lake, presence of cascading lakes, intermittent activity of supraglacial lakes, erosional activity or landslide on the dam, glacier snout conditions, potential of mass movement should be documented from the field survey. For this, it should be carried out in cooperation with all the stakeholders such as local communities, government departments, academia, agencies etc.

10. CRYOSPHERIC HAZARDS IN THE HIMALAYA

There are 2,420 glacier lakes in the Hindu Kush, Karakoram, and western Himalaya sub-regions of the upper Indus basin, 52 of which are potentially hazardous (Ashraf et al., 2012). According to ancient records, 33 GLOFs occurred in the Himalayas before the year 2000 (Richardson and Reynolds, 2000). The most devastating of them was the Cirenmaco GLOF in 1981, which damaged the China-Nepal Friendship Bridge and killed 200 people (Wester et al., 2019). Frequently or regularly, a few small-scale glacial lake outbursts occur in the mountains of HKH, although they typically go unreported because of the small scale of occurrences and isolated locales. GLOFs may even be trans-boundary, originating in one nation and travelling across large distances, affecting countries downstream. More than ten GLOF events have occurred in Nepal, all of which originated in Tibet but had a significant impact on the country's territory (Shrestha et al., 2010). The majority of moraine-dammed glacial lakes in the Nepalese Himalaya did not existed in the 1950s (Chalise et al., 2006; Haritashya et al., 2018). Many of these began as small supraglacial lakes in the mid-1950s and early 1960s, then coalesced and expanded in the 1970s (Byers et al., 2017; Haritashya et al., 2018; Komori, 2008; Watanabe et al., 2009). According to Bajracharya et al. (2020), now has approximately 2,070 glacier lakes within Nepal's territory, the majority of which were formed in the second half of the twentieth century as a consequence of rising temperatures. According to Maharjan et al. (2018), the density of lakes, both in terms of quantity and area, is higher in the eastern part of the central Himalaya.

According to ICIMOD (2011), at least 24 GLOF events have occurred in the past with the earliest dating back to 450 years ago. Out of these, 10 were due to the flood surge across China - Nepal border and 14 are believed to have occurred in Nepal. At least five GLOFs are documented that occurred since 1921 in the Kanchenjunga region of Tamor basin using field and remote sensing approaches, which are not recorded earlier (Byers et al., 2020). Similarly, five GLOFs have been reported in the past few years, i.e., the Seti river flood of May 5, 2012 (Kargel et al., 2013), the Langmoche lake flood of April 25, 2015 (Byers et al., 2017), the Lhotse GLOF of 2015 and 2016 (Rounce, Byers, et al., 2017) and Langmale GLOF of April 20, 2017 (Byers et al., 2018). The list of GLOF events documented in Nepal is shown in Figure 4. An enormous debris deposit across Pokhara Valley, a very high magnitude event, as indicated by geomorphological investigations was the first known GLOF event in Nepal that took place approximately 450 years ago (ICIMOD, 2011; Ives et al., 2010; Rana et al., 2000; Yamada and Sharma, 1993). The GLOF probably originated from the north side of Mt. Machhapuchhre. However, the details of the actual damage sustained are not available and it is assumed that the damage caused was great (ICIMOD, 2011). On 3 September 1977, a small glacial lake located at a higher elevation drained into Nare Lake, which is located below Mt. Ama Dablam peak (Buchroithner et al., 1982). As a result of the rapid water inflow, the Nare Lake overtopped its end-moraine and discharged into the Imja River, ultimately flooding the Dudh Koshi valley. This GLOF caused the death of two or three lives and damaged all of the bridges located 35 kilometers downstream of the lake (Buchroithner et al., 1982; ICIMOD, 2011; Yamada and Sharma, 1993).

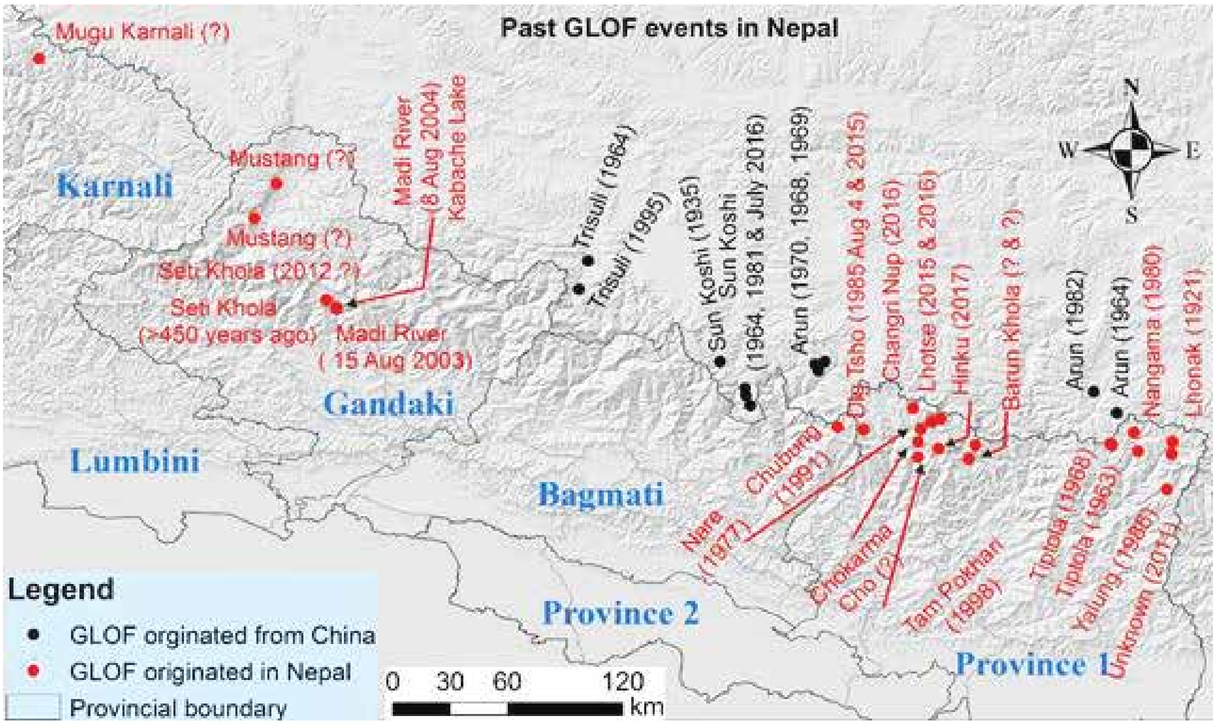


Figure 4. Glacial Lake Outburst Floods that caused damage in Nepal prepared after Bajracharya et al., 2008; Byers et al., 2020, 2018, 2017; Chand, 2020; Ives et al., 2010; Kargel et al., 2013; Rana et al., 2000; Rounce, Watson, et al., 2017; Yamada and Sharma, 1993).

A GLOF incident occurred in Tamor basin on June 23, 1980, owing to the collapse of a moraine in the Nangama Lake basin (Watanabe et al., 1998) and some concern has been also expressed for the chance of another GLOF from this lake (Byers et al., 2020). Eight persons were killed and 10 houses and four bridges were washed away by the Nangama GLOF. Villages were devastated 71 kilometers downstream of the outburst GLOF occurred on August 4, 1985, from Dig Tsho, a glacial lake dammed by the Langmoche Glacier's terminal moraine. This GLOF is the most studied and documented event till date and also marked the turning point in the study of potentially dangerous glacial lakes in Nepal and the Himalayan region. It destroyed the almost finished Namche Small Hydel plant, which was 11 kilometers from the dam, damaged tens of kilometers downstream, and claimed the lives of four or five people. Long sections of the trekking path to Mt. Everest base camp was also damaged (Bajracharya et al., 2007; ICIMOD, 2011; Vuichard and Zimmermann, 1987).

Chubung Lake in Tama Koshi basin discharged on 12 July, 1991 when its end moraine collapsed. A GLOF was triggered from Tam Pokhari Lake of Dudh Koshi basin on 3rd September, 1998 when an ice avalanche induced a surge wave and overtopped the end moraine dam. Due to moraine collapse, two GLOF events occurred in the Modi River. These two incidents occurred on the 15th of August in 2003 and the 8th of August in 2004 (ICIMOD, 2011).

A recent study identified 47 glacial lakes as potentially dangerous in three major river basins of Nepal that includes part of Tibet (China) and India that may have an impact on territory of Nepal if they burst (Bajracharya et al., 2020). Out of 47 potentially dangerous glacial lakes 21 glacial lakes are located only in Nepal and 15 lakes with priority I, three lakes categorized as priority II and three lakes categorized as priority III (Table 4). To minimize the impacts from potential outburst, Nepal government has conducted the mitigation and adaptation actions for the two large glacial lakes. Imja Lake (Figure 5) is one of the rapidly growing glacial lakes with priority I has been lowered by 3.4 m in 2016, however, it is still considered as the most dangerous glacial lake. Similarly, Tsho Rolpa glacial lake (Figure 6) in the Tamakoshi subbasins of the Dolakha district also lowered with the integration of an early warning system in the downstream region. However, there are many more lakes changing their geometry with time.

Figure 5. Imja glacial lake in Dudh Koshi basin in eastern Nepal ***(Photo: Teiji Watanabe, 2019).***

Besides glacial lake related hazards, avalanches are also common cryospheric hazards in the region. There are very limited studies related to avalanches in Nepal Himalaya, however, several events of avalanches are observed and covered by the news media. A powerful cyclone named Hudhud with a 2,000 km diameter hit the east coast of India on 12 October 2014 and then landed inland, dumping huge quantities of rains and snow on the Annapurna region and killed 43 people due to snow blizzards and avalanches on 13 October 2014. After making landfall with sustained wind speeds of 217 kilometers per hour, which contained enough moisture to drop more than a meter of snow in the Annapurna region (NASA, 2014). Between 13 October and 15 October 2014 many people were trapped by a heavy snowstorm event at Thorong La Pass (Neckel et al., 2015).

Tsho-Rolpa Glacial Lake in Rolwaling Valley ***(PC: Rakesh Kayastha)***

Figure 6. Tsho- Rolpa Glacial lake in Rolwaling Valley (above), sluice gate on the outlet of Tsho-Rolpa Glacial lake constructed for the purpose of lake lowering in 2000
(Photo: Rakesh Kayastha).

Not only the event in 2014, even on 17 January 2020, four Korean trekkers and three Nepalese guides were swept away by an avalanche at Deurali area of the famous Annapurna region (The Himalayan Times, 2020). Many such events also occurred in the Sagarmatha (Everest) region. Six Nepalese Sherpas were killed on 5 April 1970; another six climbers of French Everest Expedition died on 9 September 1974; and 15 people died on 10 and 11 May 1996. Human casualties due to snow avalanche occurred not only in the Annapurna and Sagarmatha regions of Nepal, other regions such as the Gokyo Lake area snow avalanche on 11 November 1995 killed 42 people in which 13 were Japanese trekkers. A huge avalanche on 20 October 2005 in Manang that caused the death of 18 people including foreign trekkers, local guides and porters. A Japanese climber and Nepalese guide died in an avalanche on 4 June 2011 while trying to climb the Naya Kanga peak in Langtang Valley, Rasuwa district. A leading Russian climber, died in a snow avalanche on 30 September 2011 in the Thulagi Peak, Manang district. Nine people died and 3 were missing in an avalanche in the Mount Manaslu area in 2012.

Table 4. List of potentially dangerous glacial lakes in Koshi, Gandaki and Karnali basins of Nepal and TAR, China *(Source: Bajracharya et al., 2020)*.

SN	Lake ID/Name	Rank	Description	River basin
1	GL087945E27781N	I	Less dam length, steep side slope and landslide, source glacier hanging but far from the lake.	Tamor
2	GL087934E27790N	III	Lake close to dam end but confined outlet, hanging glacier, steep side wall slope.	Tamor
3	GL087893E27694N	III	Shallow lake at steep slope and short dam length, hanging mother glacier	Tamor
4	GL087749E27816N	I	Glacier in contact, less dam length, possibilities of avalanches, landslide on outer slope of dam.	Tamor
5	GL087596E27705N	I	Lake expanding, cascading lake overflow may trigger the outburst, less dam width, erosion at end moraine.	Arun

SN	Lake ID/Name	Rank	Description	River basin
6	GL087632E27729N	III	Lake outlet close to moraine dam end (2m), high gradient dam,	Arun
7	GL087095E27829N	II	Hanging lake connected with the retreating glacier, landslide at the side wall.	Arun
8	GL087092E27798N Lower Barun	I	Possibilities of expansion of lake, calving source glacier, chances of landslide and ice avalanches at the right side wall of the lake, one lake and couple of small lakes at the at the upper catchment.	Arun
9	GL086977E27711N	I	Lake expanding towards glacier, short dam length and steep, calving source glacier, high chances of ice toppling and avalanches	Dudh
10	GL086958E27755N Chamlang	II	Hanging glaciers, high chances of ice avalanches, lake formation near the end moraine, Ice underneath the dam but the dam length is more than 500m	Dudh
11	GL086957E27783N Hongu 2	I	Hanging glacier, chances of avalanches, short dam length and steep slope with many erosional features	Dudh
12	GL086935E27838N Hongu1	I	Lake expanding towards the retreating glacier snout, hanging lakes on both side of the valley, lake outlet is close to dam end. Many cascading lakes in the lower old moraine., PDGL GL086928E27850N is at the hanging valley	Dudh
13	GL086928E27850N	I	Lake out let near to the dam end, dam outer slope is steep, cascading lake in upstream, chances of landslide and ice avalanches at upstream, may also trigger to the lake GL086935E27838N	Dudh
14	GL086917E27832N	I	Close to source glacier, short dam length and steep side slope with erosional features, Ice underneath the dam,	Dudh
15	GL086858E27687N	I	Few meters of freeboard, outer dam slope steeper, hanging source glacier, chances of landslide, ice avalanches from the head water and from right valley.	Dudh
16	GL086925E27898N Imja Tsho	I	Lake water lowered by 4m in 2016, lake expanding level reduced, ice underneath end moraine, merging of supraglacial pond	Dudh
17	GL086612E27779N Lumding	I	Lake expanding rapidly, in contact with calving glacier, 3 hanging lakes at the side valley, continues dam slope	Dudh
18	GL086476E27861N Tsho Rolpa	I	Lake water lowered in 2000, expanding rapidly with the retreat of calving source glacier, steep moraine dam and side moraine is thin and danger, hanging lake in tributary glacier.	Tama
19	GL085630E28162N	I	Lake at extreme dam end, chances of landslide from the right side wall and ice avalanches from the hanging source glacier.	Trishuli
20	GL084485E28488N Thulagi	I	Large lake and expanding on the debris covered source glacier, possibility of landslide and snow avalanches from the side walls, evidences of subsidence of old and compact end moraine.	Marsya-ngdi
21	GL082673E29802N	II	Shallow lake but close to crest, overhanging boulder protecting the erosion of the dam, hanging source glacier with many crevasses.	Mugu

Coseismic avalanches and rockfalls induced by the 25 April 2015 Gorkha earthquake destroyed the Langtang village and killed more than 350 people (Kargel et al., 2016). The deposited volumes by this avalanche and succeeding rockfalls was about 7.65 × 10^6 m^3 (Fujita et al., 2017) and deposited over the Langtang Valley. The earthquake also triggered another massive avalanche from Pumori that swept through Everest Base Camp and killed 18 people with several seriously injured (NGS, 2015).

These statistics showed that cryospheric hazards, i.e., avalanches and GLOFs are prevalent in the Himalayan regions of Nepal and a significant number of people lost their life frequently. Death of people can be prevented with real time weather forecast and strengthening the capacity of the local people including lodge owners, local government officials, trekkers, and local guides. Similarly, GLOF hazard management plan need to be formulated and integrated in development for reducing the risk from potentially dangerous glacial lakes. Therefore, it is essential to strengthen the capacity of GLOF and snow hazard risk reduction among the local government officials and political leaders of the rural municipalities, local lodge owners, trekkers, local people, and related stakeholders in the higher Himalayan region to minimize the damages and losses due to GLOF and snow related hazards in the region.

11. STATUS OF GLACIAL HYDROLOGY AND ITS FUTURE IMPLICATIONS

The Himalayas play a crucial role in regional hydrology, it encompasses the headwaters of the Ganges, a major river of Asia. It maintains seasonal water availability by supplying meltwater from upstream glacier ice and snow, and it provides water for agriculture, energy generation, industry, and drinking water supply. Since the previous few decades, the cryospheric regime has undergone dramatic changes, which are mostly related to rising temperatures (Liu and Chen, 2000; Xu et. al., 2009; Radi et al, 2013; Shea et al., 2015; Bolch et al., 2019). Huss and Hock (2018) analyzed global scale hydrological response to glacier mass loss in 56 large-scale glacierized river basins until 2100 using Global Glacier Evolution Model (GloGEM). GloGEM was used to estimate glacial runoff for each glacierized basin by incorporating all important glaciological processes such as mass accumulation and ablation, as well as variations in glacier extent and surface elevation. The results of this model predicted a rise in annual glacier runoff until mid-century, followed by a continuous reduction thereafter in the glacierized basins of the HMA. During the summer season, monsoon rainfall contributes significantly to streamflow contribution in central Himalayan basins; but, during dry seasons, snow and ice melt contribute significantly to river discharge (Wu, 2005; Panday et al., 2011; Rajbhandari et al., 2016).

Different modelling concepts and approaches have been used to understand the future hydrological response in the Nepal Himalaya. Douglas et al. (2016) used the Glacier-Evolution and Runoff Model (GERM), a fully distributed glacio-hydrological model by modifying and integrating the debris-cover algorithm in the upper Khumbu watershed of the Koshi River basin. They found that under several climatic scenarios, the continued mass and volume loss of 60-90% till the end of the century. The runoff was expected to grow at first, then decline, with runoff in 2100 expected to be 8% lower than the present. Using remote-sensing techniques, Xiang et al. (2018) projected a 10.4% loss in the glacier area from 1975 to 2010 at a rate of 0.30% a^{-1}, with increasing melting since 2000 (0.47% a^{-1}) in the Koshi River basin.

Using remote sensing and GIS technology, Donghui et al. (2014) achieved comparable results. They calculated that glacier area loss in the Koshi River watershed was 0.59 ± 0.17% a^{-1} between 1976 and 2009. Between 1976 and 2009, the number of glaciers declined from 2206 to 2061, and many glaciers with an area of less than 1 km^2 vanished. A few glaciers split into two or more single glaciers. From 1976 to 2009, the glacier area change on the south side of the Himalayas (20.3 ± 5.6%) was slightly faster than on the north side of the Himalayas (18.8 ± 5.6%), particularly from 2000 to 2009. Since the 1970s, the Kangwure Glacier in the Koshi River basin has lost 34.2% of its surface area, 48.2% of its ice volume, and 7.5 meters of an average thickness (Linglong et al., 2010). Similarly, Nepal (2016) used the J2000 model to conduct glacio-hydrological modeling in the Koshi

River Basin, estimating that snow and glacier melt contributes 34% of the total flow on an annual basis. Furthermore, during the pre-monsoon season, the contribution was roughly 63% (March to May). According to this analysis, a 13% increase in yearly discharge is projected by mid-century, followed by a modest decline.

Kayastha et al. (2020) used the Glacio-hydrological Degree-day Model (GDM), a gridded and distributed glacio-hydrological model in three glacierized river basins of Nepal Himalayas viz. Marsyangdi, Trishuli and Tamor River basin. GDM is a glacio-hydrological model based on the temperature index modeling approach which is capable of simulating hydrological component contributions on river discharge. The model is a simplification of complex phenomena with the minimum data requirements. In the Marsyangdi River basin, snowmelt contributes 7%, while in the Trishuli River basin, it contributes about 13%. Similarly, in the Tamor River basin, ice melt contributes 6% of river flow, while in the Marsyangdi River basin, it contributes 12%. Baseflow varies from 41% in the Marsyangdi River basin to 45% in the Trishuli River basin, with rainfall contributing 29% to river flow in the Trishuli River basin and 39% in the Tamor River basin as shown in Figure 7.

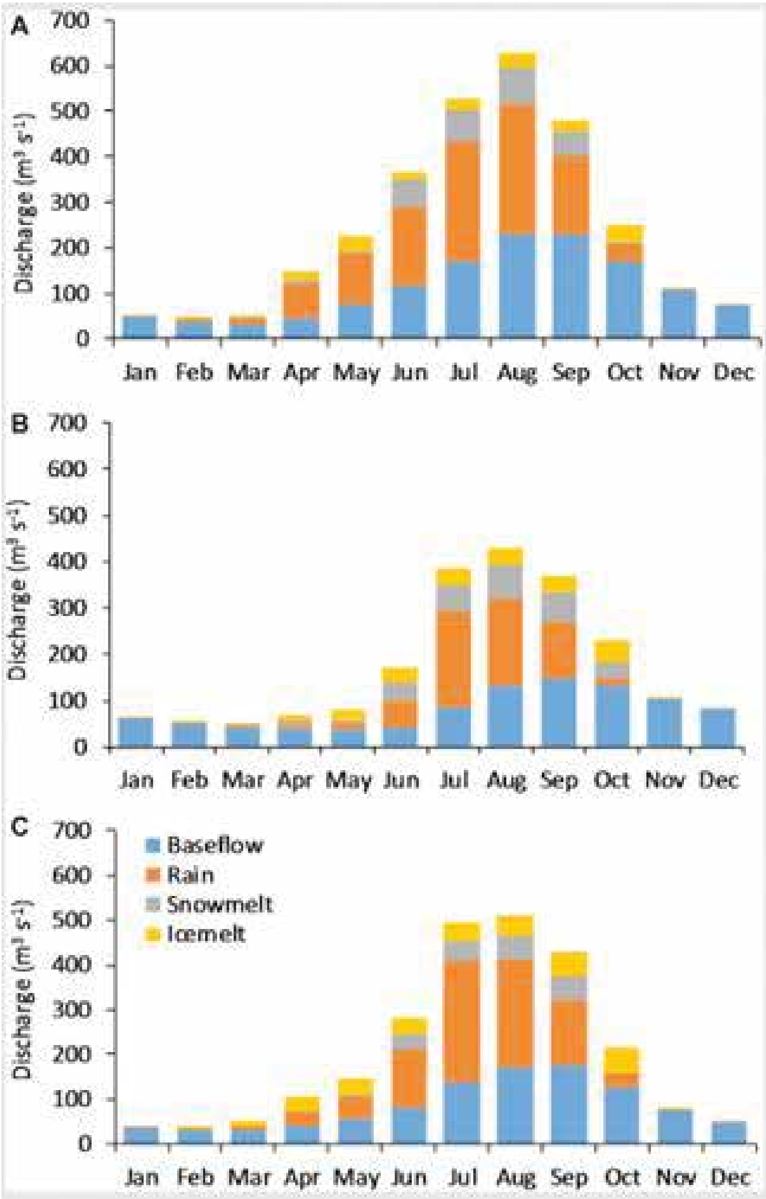


Figure 7. Monthly partition of snowmelt, ice melt, rain, and baseflow contributions in (A) Tamor (B) Trishuli and (C) Marsyangdi River basins.

A similar result is estimated by Racoviteanu et al. (2013) using an ablation model where the ice melt contribution is 9% at Betrawati, downstream of Trishuli River basin. Panday et al. (2013) used the snowmelt runoff model to find that the average contribution of snowmelt in river flow in the Tamor River basin at the Majhitar from 2002 to 2006 was 29.7 ± 2.9% (including 4.2 ± 0.9% from snowfall that melts quickly), while rainfall contributed 70.3 ± 2.6%. For future hydrological responses under different climates scenarios, Kayastha and Kayastha (2020) used GDM in Trishuli and Marsyangdi River basins where the discharge in both glaciated basins is projected to increase till 2100. The ice and snowmelt contributions in both basins are projected to decrease due to increases in the temperature and change in precipitation.

Similar studies have been carried out in the Koshi River basin covering Nepalese and Chinese territories using GDM by Khadka et al. (2020). For the RCP 4.5 and 8.5 scenarios, the average glacier area change in all sub-basins from 2021 to 2100 is estimated to decrease by 65 and 85%, respectively, while the average glacier volume change is estimated to decrease by 76 and 86%. After 2060, the projected discharge in all sub-basins indicates a rising trend in pre-monsoon and monsoon seasons and a decreasing trend in post-monsoon and winter seasons, potentially leading to wetter wet seasons and drier dry seasons as shown in Figure 8. In most of the sub-basins, the peak flow shifts from August to July.

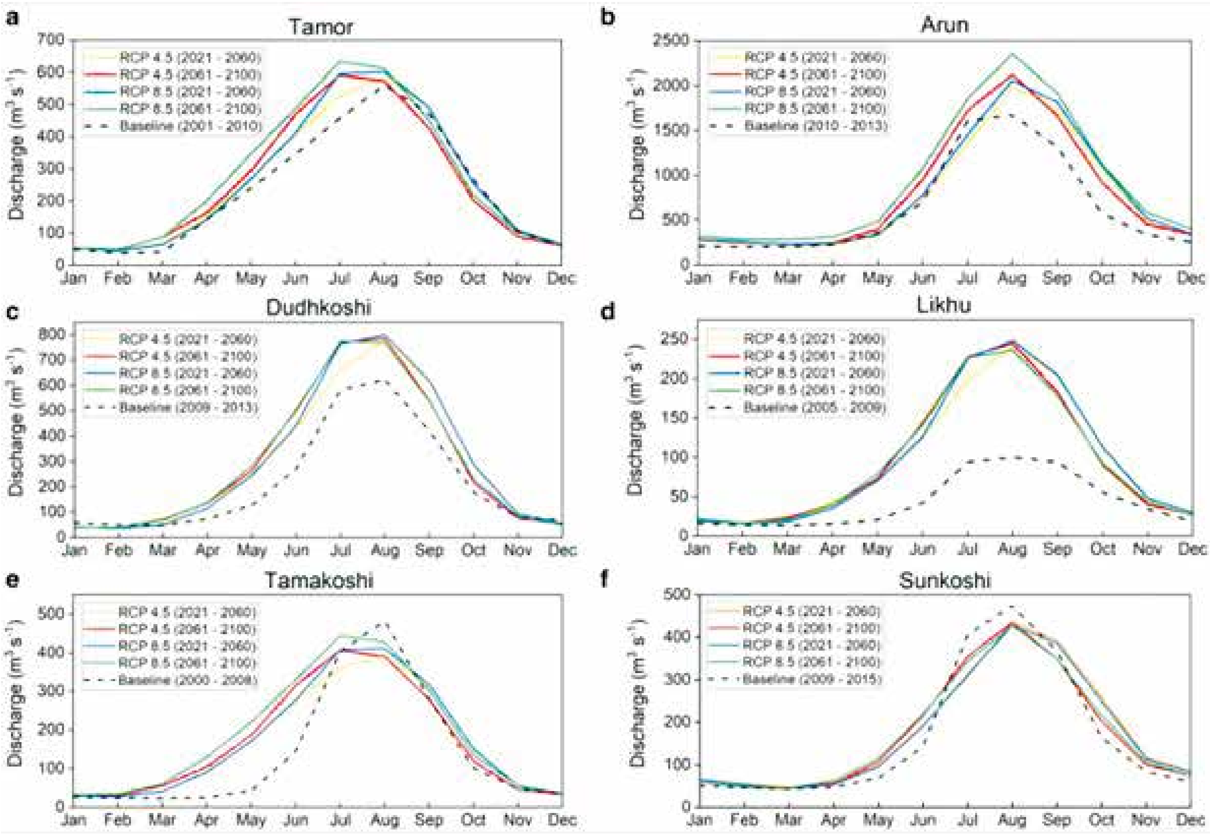
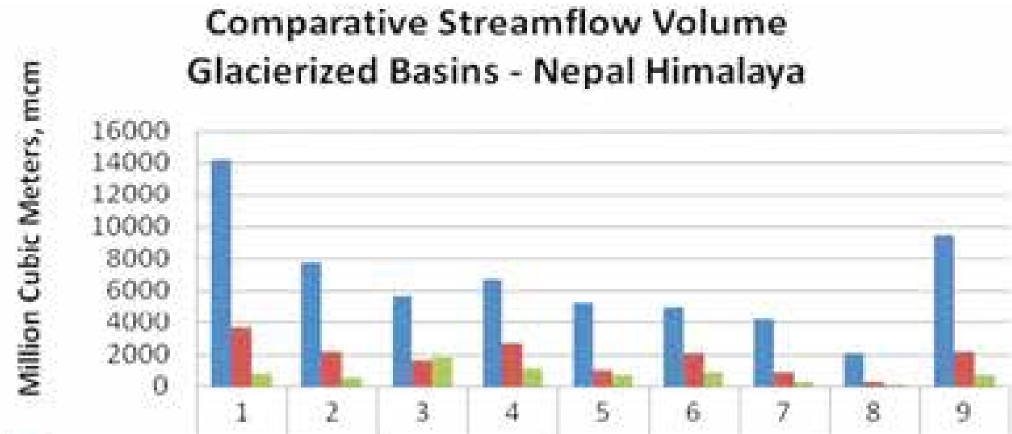


Figure 8. Monthly average simulated discharge in the Tamor (a), Arun (b), Dudhkoshi (c), Likhu (d), Tamakoshi (e), and Sunkoshi (f) sub-basins for two future reference time periods: 2021–2060 and 2061–2100 under RCP 4.5 and RCP 8.5 scenarios compared to baseline discharge.

Alford and Armstrong (2010) estimated that the contribution of annual glacier meltwater to annual streamflow into the Ganges Basin from glacierized catchments of the Nepal Himalaya is estimated to be around 4% of the total annual streamflow volume of Nepal's rivers. The contribution of glaciers to total observed streamflow in the basin in which they are located varies greatly (Figure 9), ranging from over 30% in the Budhi Gandaki basin to around 2% in the Likhu Khola basin, with an average of about 10%. This amount corresponds to around 4% of the overall mean annual projected volume of 200 million cubic meters for Nepal's rivers.



	1	2	3	4	5	6	7	8	9
Basin	14149	7705	5624	6672	5192	4918	4153	2091	9510
4-6 K m	3618	2197	1682	2668	1007	2130	829	248	2194
Glacier Melt	747	491	1791	1106	698	869	253	81	723

Figure 9. In the Nepal Himalaya, a histogram depicting the relative annual streamflow, mcm/yr, for Basin Total, 4000-6000 m Altitudinal Belt, and Glacier Melt among glacierized gauged basins. 1. Bheri, 2. Kali Gandaki, 3. Budhi Gandaki, 4. Marsyangdi, 5. Trisuli, 6. Dudh Kosi, 7. Tama Kosi, 8. Likhu, 9. Tamor are the catchment basins.

Glacio-hydrological research studies in Himalayan catchments indicate an increase in an annual runoff because of increased precipitation and increased glacier melt in the future (Immerzeel et al., 2013; Lutz et al., 2014). Compared to the western Himalayas, the snowmelt period is longer in the eastern Himalayas (Panday et al., 2011). Different modelling approaches are being used to understand the glacier response on present and future climate scenarios. These different approaches to estimate the glacier contributions in water resources are based on simple to complex modelling schema using different climate models and scenarios. Basins to regional scale glacio-hydrological studies have been carried out to understand the hydrological component contributions. The glacier contributions on river flow is supposed to increase in the mid-century from the glacier melt and on long term water supply tend to decrease causing water stress in the Himalayan region. The findings of different studies are vital in improving the understanding of modelling approaches regionally and locally. Detailed glacio-hydrological investigation should be carried out in nineteen glacierized river basins of Nepal Himalaya to estimate the present and future hydrological regime and component contributions. With increase in the monitoring stations in the high Himalaya regions could minimize the knowledge gaps and uncertainty and which will be effective to address the water balance component for the water management perspectives.

12. POLICIES AND INSTITUTIONAL ARRANGEMENT ON CRYOSPHERIC STUDIES IN NEPAL

The importance of the study of snow, glaciers and glacial lakes in Nepal was felt by the government of Nepal when a GLOF occurred on 4 August 1985 in Khumbu region. On the fine day during the monsoon period, the Dig Tsho Glacial Lake was burst out due to a huge ice mass of the adjacent glacier fell into the lake. Such studies were initiated in Nepal. The National Water Plan - 2005 mentioned the necessity of study and monitoring of snow, glacier and glacier lakes in Nepal. The first policy related with such studies in Nepal is the National Adaptation Program of Action (NAPA) to Climate Change 2010 in which it stated that, glacier and glacial lakes should be studied and a few potentially dangerous glacial lakes should be monitored and lowered water level. Then the Climate Change Policy – 2019 also mentioned the necessity of lowering water level of potentially dangerous glacial lakes and monitoring of glacial lakes.

Nepal Climate Change Policy-2019 has been formulated by the Ministry of Forest and Environment in Nepal as the centerpiece of Nepal's response to climate change with a vision of limiting the impacts of climate change through environmental conservation and sustainable development. The policy outlined the climate change adaptation and disaster risk reduction, low carbon development and climate resilience, access to financial resources and utilisation, capacity building, peoples' participation and empowerment, study and research, technology development, transfer and utilisation, climate-friendly natural resources management. The policy aims to establish a climate change center; initiate community-based local adaptation actions; preparation of a national strategy for carbon trade; formulation and implementation of a low-carbon economic development, assessment of climate change impacts and promotion of climate change adaptation and effective measures to address impacts of climate change.

Nepal became a Party to the United Nations Framework Convention on Climate Change (UNFCCC) in 1994 and thereafter is continuously working in climate change adaptation and mitigation. National Adaptation Program of Action (NAPA) identified the adaptation projects in 2009 and many of them in are operation. The community forest, agroforestry and private forest development program of Nepal is playing a role in reducing greenhouse gas emissions, carbon sequestration and climate change adaptation. Similarly, the Climate Change Council was constituted under the chairmanship of the Prime Minister and consisting of experts in 2009 to maintain policy coordination in the area of climate change. The Climate Change Management Division has been established in the Ministry of Forests and Environment and designated as a focal point to coordinate with different levels and sectors of climate change. An implementation framework of Local Adaptation Plans for Action (LAPA), was developed in 2011 to integrate the climate change into local development plan, Community Based Adaptation Plan is being implemented at community level. Nepal has prepared the Third National Communication Report for UNFCCC in 2021 with elaboration of greenhouse gases inventory, adaptation and mitigation actions taken and planned.

Having sufficient policies for adaptations and mitigation strategies, the implementation of policies is found to be weak. Lack of studies, research and basic data about the impact of climate change effect and potential loss or damage resulting from climate-induced disasters, failures to mainstream the climate change issues into the overall development process are the major problems and challenges in the area of climate change management. Additionally, building a climate resilient society through climate change adaptation and mitigation in a mountainous rugged terrain and economically least developed country like Nepal is challenging. There is a lack of specific adequate policies related to the cryosphere region of Nepal, which is the source of major rivers. Most hydropower development projects do not consider the cryospheric hazards and its melt water contribution in the power production. Several roads, bridges and other infrastructures are developing after the federalism in the country, while no adequate consideration of the cryosphere has been observed. This could cause the failure of multi-million projects with changes in water availability and potential cryospheric related hazards. Therefore, cryospheric specific climate change policy is required and needs to be mainstreamed in all development projects in the downstream regions of glaciated catchments.

The first study of snow and glaciers was led by the Department of Hydrology and Meteorology (DHM), Government of Nepal in 1987 by establishing stations in the higher mountain regions from east to west Nepal. The Government of Nepal designated the DHM as the government body to study and monitor snow, glaciers, glacial lakes and permafrost in Nepal. The fruitful cooperation between the government of Nepal and the Federal Republic of Germany (1987 – 1997) resulted in the establishment of "Snow and Glacier Hydrology Unit (SGHU)", a sub-division in the Department of Hydrology and Meteorology (DHM). With the technical and financial support from the Government of Germany, the DHM established six hydro-meteorological stations from east to west in Nepal (Figure 10) in between 1987 to 1992 and started to collect hydro-climatic data from those stations.

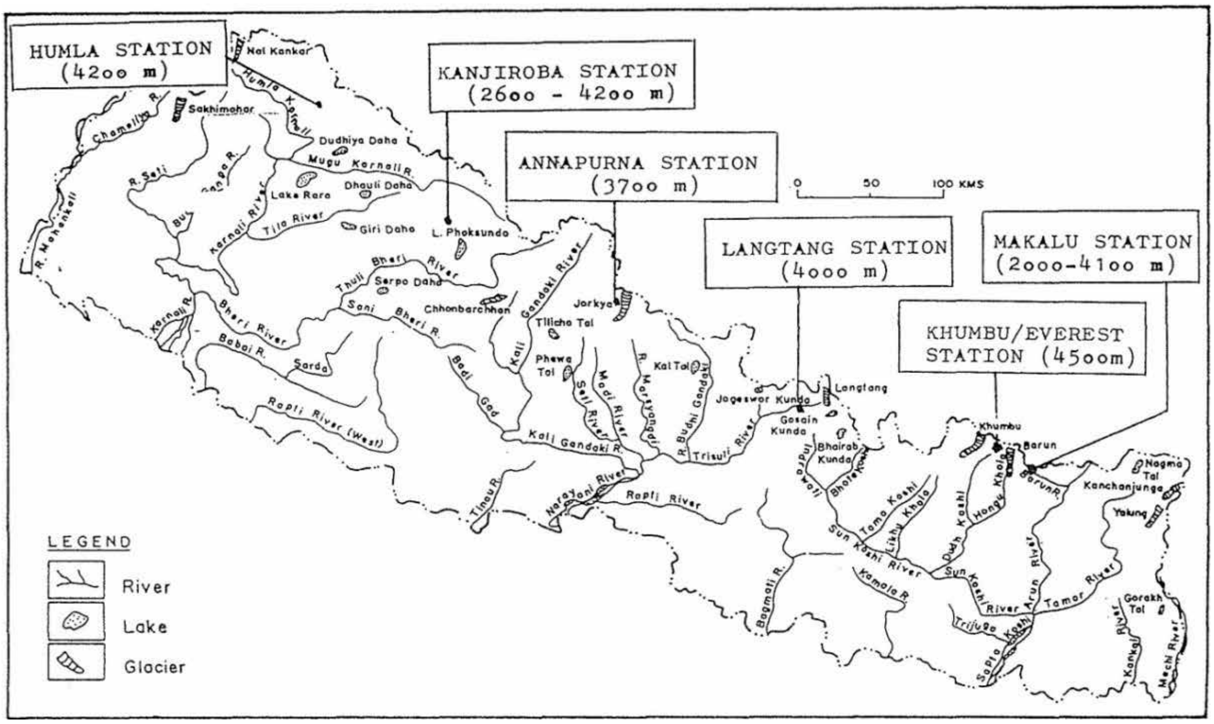


Figure 10. Location of six hydro-meteorological stations of SGHU, DHM in June 1992 (from Grabs and Pokhrel, 1992).

The Himalayan Cryosphere, Climate and Disaster Research Center (HiCCDRC), Kathmandu University is also a major institution in Nepal for studying snow, glacier, glacial lakes and permafrost in Nepal. The International Centre for Integrated Mountain Development (ICIMOD) is an international agency in Nepal which also study these cryospheric components in Nepal. Recently, Water resources Research and Development Centre, an institution of the Government of Nepal has also initiated to work in cryosphere of Nepal Himalaya. Different universities and research institutions in Japan, America, Europe, China have also carried out many glaciological studied in Nepal in the past.

13. CONCLUSIONS AND RECOMMENDATIONS

a. Conclusions

Cryospheric region is the source of freshwater for millions of people in downstream regions and reducing the coverage of cryospheric components pose significant risks to the stability of water resources in the Himalayan region. Past researches on snow, glacier, glacial lake and permafrost in Nepal are reviewed thoroughly and shows that the impacts of climate change on cryosphere is clearly seen. Although changes in glacier area and volume is studied using satellite remote sensing data, only a few glaciers are studied with the field investigation. The collection of scientific information from the previous studies reveals that Himalayan glaciers are in a state of emergency in terms of future water availability, potential risk from glacial lake development and GLOFs, and changes in regional and local precipitation patterns. There is still a large uncertainty due to lack of studies and gaps in data to predict climate change impact. Physical manifestations of climate change in the Himalayas include locally and regionally significant increases in temperature, as well as a rise in the frequency and duration of extreme events. Similarly, the potential risk from change in the cryosphere is generalized, however, estimation of the level of risk due to climate change related hazards in mountain regions is still poorly developed. Earlier studies are either regional based covering the whole HMA region, Hindu-Kush Himalaya-Karakorum, small catchment scale, or glacier and glacial lake specific, however, comprehensive studies that cover the Nepal Himalaya are poorly documented. This can have uncertainties in implication posed by climate change. However, based on available studies in this region, several inferences can be drawn.

The decrease in snow and glacier cover and ultimate decrease in river flows will have implications on livelihood, ecosystem and economy at local, national and regional levels mainly in dry periods. Nepal is highly dependent on water resources from the glaciers, snow and permafrost melt and recently developing several run off based hydropower plants that receive water from them. The decrease in snow and glacier cover and ultimate decrease in river flows will have implications on hydropower generation, livelihood, ecosystem and economy at local, national and regional levels mainly in dry periods. Hydropower is a clean source of energy and can contribute in reducing the greenhouse gases and mitigate climate change, while it can significantly contribute in the country's economy if Nepal can produce enough hydropower for exporting neighbouring counties. However, due to increasing temperature and changes in precipitation patterns, the cryospheric region is reducing its extent and water availability will not be long lasting, which can reduce the hydropower generation capacity. Additionally, the frequency of climate induced disasters is increasing in Himalayan region, which may have direct and indirect impact on downstream regions. There are 2,070 glacial lakes among which 21 are potentially dangerous but water level of only two of them have been lowered till now; Tsho Rolpa in 2000 and Imja Glacier Lakes in 2016. The knowledge of risk from potential impact of climate change in different aspects of the cryospheric region of Nepal is limited and it is very difficult to predict the actual hazard from GLOFs, however, serious damage has been observed in several past events.

In brief the following implication can be expected from increasing global temperature in the Nepal Himalaya:

Short-term

- Increasing frequency of extreme climatic events, i.e., extreme precipitations, warm days, cold days, drought
- Changes in the snowfall patterns, its extent and intensity
- Formation and development of large glacial lakes dammed by the unstable moraine
- Increase in glacier meltwater discharge to some extent

Medium-term

- Continued increase in frequency of extreme climatic events
- Loss of the glacier area, changes in Himalayan landscape and disappearance of snow-capped mountains
- Continuous increase in glacier meltwater discharge and reaching to maximum discharge
- More water will be available for hydropower generation, agricultural and other purposes with increase in river discharge
- Continued development of potentially dangerous glacial lakes
- Increase in frequency of GLOFs with continuous increase in number and area of the glacial lakes

- Increase in cryospheric related hazards and loss of glacier and snow covered area will reduce the number of tourists in the Himalayan region. Tourism is one of the main sources of income country and is expected to affect the country's economy.

Long-term

- Disappearance of glaciers and snow covered landscapes of the Himalayas
- Changes in forms of precipitation from snow and rain in the much higher elevations
- Increase in flash flood events, erosion and sedimentation due to changes in the form of precipitation
- Decline in river discharge due to loss in glacier area that will continued in the long-run and impacts on livelihood, ecosystem and agriculture
- Decrease in capacity of hydropower generation and ultimately its reduction to GDP contribution
- Glacial lakes will reach their maximum extent after loss of all glacier area and limited chances of further growth
- Impacts on the country's economy with continued reduction in number of tourists
- Extinction of endangered species of the Himalaya and loss of biodiversity
- Conflicts between communities, districts, and provinces due to scarcity of water resources, decline in agricultural production and changes in livelihood.

b. Recommendations

This report is based on existing available studies in the Nepal Himalayas and conclusions drawn from this study might be useful for policy makers, development communities, civil society organizations, governmental and non-governmental organizations, academic researchers, journalists, and other stakeholders. This piece of work presents scenarios on the implication of climate change in the cryospheric region of Nepal Himalaya and will be helpful to raise awareness among the relevant stakeholders. Findings of this study will be helpful to governmental, non-governmental, and concerned agencies for future program development on efforts in minimizing the impacts of climate change and provide opportunities for new aspects of academic research. The impacts of climate change on the Himalayan cryosphere are increasing rapidly and urgently need to be considered seriously in development activities. Otherwise, its negative impacts will affect water resources, hydropower, tourism, and increase the risk of cryospheric hazards which will severely impact the overall development of Nepal. In order to tackle the impacts of climate change on the Himalayan cryosphere in Nepal the following recommendations are suggested:

Government Level

1. Governments (three tiers) need to initiate the establishment of a research platform and strengthen the capacity of existing institutions to conduct and monitor the Himalayan Cryosphere. Only a few glaciers of Nepal have been studied at present which needs to be increased so that at least representative glaciers from all 19 glacierized sub-river basins of Nepal should be studied. Also, permafrost studies should be carried out inw those sub-river basins to know its extent and contribution in the river discharge.

2. Government should encourage academic institutions, civil societies, individual researchers and the private sector to become involved in cryospheric studies and climate change mitigation and adaptation actions. Regular monitoring of glacial lake and its potentiality of burst must be investigated for the glacial hazard using field and ground validation and. Remote sensing approach should be implemented

for regular and repeated monitoring of glacial lakes, glaciers and snow cover.

3. Local and provincial governments should identify their priority and seek help from the federal government and other aid agencies. The identified potentially dangerous glacial lakes need to be mitigated based on their priority of risk. It is necessary to regularly monitor structural intervention to ensure the safety of downstream communities.

4. Out of 2,070 glacial lakes; 21 are potentially dangerous and out of it water level of only two lakes namely, Tsho Rolpa and Imja Glacial Lakes have been lowered till now. Water level of other dangerous glacial lakes should be lowered gradually by the government in collaboration with aid agencies and researchers in the field. Also, it is essential to install an early warning system downstream of those potentially dangerous glacial lakes.

5. Very few weather stations are available at high altitudes (above 3,000 m a. s. l.) in Nepal at present. Snow monitoring and weather stations at high altitudes should be increased to at least 23 in all 19 glacierized sub-river basins of Nepal with remote data transmission facility. It will be useful to reduce risk and associated hazards from snow avalanches in the mountains Himalayas and equally useful in glacier and glacio-hydrological studies.

6. Snow collection and rainwater harvesting schemes should be encouraged in the mountains and the Himalayas for the sustainable use of water resources for irrigation and household purposes.

7. Trans-boundary regional cooperation needs to be established for cryosphere monitoring, disaster risk management and climate change adaptation strategies as several Nepalese rivers originate from Tibet (China) and enter India in their downstream region.

8. Develop short-term and long-term water management and cryospheric specific disaster management policies and plans in different climate change scenarios and update them on a regular basis which will help to develop water related infrastructures in the downstream regions with consideration of different scenarios of climate change and climate induced disasters in the downstream regions.

9. Preparedness for disasters and risk mitigation should be considered an essential aspect of water resource management. Integrated water resources management (IWRM) should be expanded up from watersheds to river basins to account for future climate change scenarios to include the cryospheric region. Particular emphasis should be paid to water distribution for households, agriculture, and ecosystems. In mountain areas, water storage based on local methods should be encouraged. Future climate change scenarios should be included in IWRM, which should be scaled up from watersheds to river basins.

10. Government needs to regulate the development infrastructures in the downstream region to be affected by water from the cryospheric region and possible GLOFs in the future.

11. Provide incentives to communities and individuals to encourage them for increasing agricultural and livestock production in the higher altitudes and prepare them for potential impacts of climate change.

12. Priority should be given for mitigation and adaptation actions to minimize the potential impacts caused by climate change, change in water availability, and disasters.

13. To overcome challenges and gaps in cryospheric risk and climate change adaptation, Local Disaster and Climate Resilience Planning (LDCRP) should include the cryospheric hazard in its plan. The idea behind LDCRP is to identify vulnerability, hazards, and risk through the participatory process of local communities and design and implement those plans to build resilient communities.

14. Cryopsheric risk-informed budget planning practice should be adopted at all levels and should be based on vulnerability, hazard and risk assessment.

Development Agencies and Civil Societies

1. Glacio-hydrological regime of all 19 glacierized sub-river basins should be studied using a suitable glacio-hydrological model so that contributions of snowmelt and ice melt in discharge is known and future scenarios of discharge can be ascertained using downscaled future climate data. The outcomes of the results need to be shared with governments to help for future strategies.

2. Civil societies are expected to carry out awareness and advocacy for climate and cryosphere related policies, acts and regulations for better water and disaster management at different levels. Credible, up-to-date scientific knowledge is essential for the development of a climate change policy, including adaptation and mitigation strategies by interlinkage of upstream and downstream communities.

3. Community-led local knowledge, innovations and practice should be strengthened for climate change adaptations by empowering communities with the decision-making processes and participatory technology.

4. Development agencies are expected to develop programs in disaster resilient structures, improving livelihood of mountain and downstream communities, support local communities in their capacity development on resilience building, and establish/promote research platforms.

5. Support the government in integration of cryospheric hazards on local level Disaster Risk Reduction Management (DRRM) plans, i.e.; LDCRP and District Disaster Preparedness and Response Plan (DPRP), Local Adaptation Plan of Action (LAPA), Province level climate change adaptation strategic action plan and promote role of disaster related institutions as prescribed by DRRM Act 2074.

Private sector

1. Private sector should collaborate with local, provincial and federal governments in developing mitigation and adaptation measures for the higher Himalayan region and in its downstream region.

2. Increase investment for climate resilient infrastructures that ensure the safety and increase resilience capacity of local communities.

3. Invest and promote research platforms for cryospheric research, glacio-hydrological modeling, early warning system and innovation for research techniques and instruments and measures of livelihood enhancement.

4. Provide opportunities of micro-financial access to local communities for livelihood enhancement and to increase their resilience capacity.

5. Private sector should advocate for and invest in a weather information system for adopting preparedness measures from cryospheric risk.

❑❑❑

14. REFERENCES

Acharya, A. & Kayastha, R B (2019). Mass and Energy Balance Estimation of Yala Glacier (2011–2017), Langtang Valley, Nepal. Water, 11, 6. Doi: 10.3390/w11010006

Ageta, Y., Higuchi, K. (1984). Estimation of Mass Balance Components of a Summer-Accumulation Type Glacier in the Nepal Himalaya. Geogr. Ann. Ser. A, Phys. Geogr. 66, 249. https://doi.org/10.2307/ 520698.

Alford, D. and Armstrong, R. (2010) The role of glaciers in stream flow from the Nepal Himalaya. The Cryosphere Discussions 4, 469–494. doi:10.5194/ tcd-4-469-2010, 2010.

Ashraf, A., Naz, R., and Roohi, R. (2012). Glacial lake outburst flood hazards in Hindukush, Karakoram and Himalayan ranges of Pakistan: Implications and risk analysis. Geomatics, Natural Hazards and Risk, 3(2), pp. 113–132. https://doi.org/10.1080/19475705.2011.615344.

Azam, M.F., Wagnon, P., Berthier, E., Vincent, C., Fujita, K., Kargel, J.S., 2018. Review of the status and mass changes of Himalayan-Karakoram glaciers. J. Glaciol. 64, 61–74. https://doi.org/10.1017/jog.2017.86.

Bajracharya, B., Shrestha, A. B., and Rajbhandari, L. (2007). Glacial Lake Outburst Floods in the Sagarmatha Region. Mountain Research and Development, 27(4), pp. 336–344. https://doi.org/10.1659/mrd. 0783.

Bajracharya, Maharjan, S., Shrestha, F., Bajracharya, O., Baidya, S., 2014. Glacier Status in Nepal and Decadal Change from 1980 to 2010 Based on Landsat Data. Kathmandu, ICIMOD.

Bajracharya, S.R., Maharjan, S.B., Shrestha, F., Sherpa, T.C., Wagle, N., Shrestha, A.B., 2020. Inventory of glacial lakes and identification of potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali River Basins of Nepal, the Tibet Autonomous Region of China and India.

Benn, D.I., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L.I., Quincey, D., Thompson, S., Toumi, R., Wiseman, S., 2012. Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards. Earth-Science Rev. 114, 156–174. https://doi. org/1 0.1016/j. earscirev.2012.03.008.

Bhattacharya, A., Bolch, T., Mukherjee, K., King, O., Menounos, B., Kapitsa, V., Neckel, N., Yang, W., Yao, T., 2021. High Mountain Asian glacier response to climate revealed by multi-temporal satellite observations since the 1960s. Nat. Commun. 2021 121 12, 1–13. https://doi.org/10.1038/s41467-021-24180-y.

Bolch, T., Kulkarni, A., Kaab, A., Huggel, C., Paul, F., Cogley, J.G., Frey, H., Kargel, J.S., Fujita, K., Scheel, M., Bajracharya, S., Stoffel, M., 2012. The State and Fate of Himalayan Glaciers. Science (80). 336, 310–314. https://doi. org/10.1126/science.1215828.

Bolch, T., Pieczonka, T., Benn, D.I., 2011. Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery. Cryosphere 5, 349–358. https://doi.org/10.5194/tc-5-349-2011.

Bolch, T., Shea, J.M., Liu, S., Azam, F.M., Gao, Y., Gruber, S., Immerzeel, W.W., Kulkarni, A., Li, H., Tahir, A.A., Zhang, G., Zhang, Y., 2019. Status and Change of the Cryosphere in the Extended Hindu Kush Himalaya Region, in: The Hindu Kush Himalaya Assessment. Springer International Publishing, Cham, pp. 209–255. https://doi. org/10.1007/978-3-319-92288-1_7.

Buchroithner, M. F., Jentsch, G., and Wanivenhaus, B. (1982). Monitoring of recent geological events in the Khumbu area (Himalaya, Nepal) by digital processing of Landsat MSS data. Rock Mechanics Felsmechanik Mécanique Des Roches, 15(4), pp. 181–197. https://doi.org/10.1007/BF01240589.

Byers, A. C., Byers, E. A., McKinney, D. C., and Rounce, D. R. (2017). A Field-based Study of Impacts of the 2015 Earthquake on Potentially Dangerous Glacial Lakes in Nepal. HIMALAYA, the Journal of the Association for Nepal and Himalayan Studies, 37(2), pp. 26–41. Retrieved from http://digital commons.macalester. edu/ himalaya/vol37/iss2/7.

Byers, A. C., Rounce, D. R., Shugar, D. H., Lala, J. M., Byers, E. A., and Regmi, D. (2018). A rockfall-induced glacial lake outburst flood, Upper Barun Valley, Nepal. Landslides, 2012 (October). https://doi.org/ 10.1007/ s10346-018-1079-9.

Byers, A.C., Chand, M.B., Lala, J., Shrestha, M., Byers, E.A., Watanabe, T., 2020. Reconstructing the History of Glacial Lake Outburst Floods (GLOF) in the Kanchenjunga Conservation Area, East Nepal: An Interdisciplinary Approach. Sustainability 12, 5407. https://doi.org/10.3390/su12135407.

Chalise, S. R., Shrestha, M. L., Bajracharya, O. R., and Shrestha, A. B. (2006). Climate change impacts on glacial lakes and glacierized basins in Nepal and implications for water resources. Climate Variability and Change-Hydrological Impacts, IAHS Publ (November), pp. 460–465.

Chand, M.B., 2020. Development of glacial lakes in the Everest and Kanchenjunga regions, Nepal Himalaya. Hokkaido University.

Chand, M.B., Kayastha, R.B., 2018. Study of thermal properties of supraglacial debris and degree-day factors on Lirung Glacier, Nepal. Sci. Cold Arid Reg. 10, 357–368. https://doi.org/10.3724/ SP.J.1226.2018.00357.

Chand, M.B., Kayastha, R.B., Parajuli, A., Mool, P.K., 2015. Seasonal variation of ice melting on varying layers of debris of Lirung Glacier, Langtang Valley, Nepal. Proc. Int. Assoc. Hydrol. Sci. 368, 21–26. https://doi.org/10.5194/piahs-368-21-2015.

Chand, M.B., Watanabe, T., 2019. Development of Supraglacial Ponds in the Everest Region, Nepal, between 1989 and 2018. Remote Sens. 11. https://doi.org/10.3390/rs11091058.

Chevallier, P., Pouyaud, B., Suarez, W., and Condom, T. (2011). Climate change threats to environment in the tropical Andes : glaciers and water resources. Regional Environmental Change, 11, pp. 179–187. https://doi.org/10.1007/s10113-010-0177-6.

DHM, 2017. Observed Climate Trend Analysis in the Districts and Physiographic Regions of Nepal (1971-2014). Department of Hydrology and Meteorology, Kathmandu.

Donghui, S., Shiyin, L. I. U., Yongjian, D., Lizong, W. U., Wei, D., Wanqin, G. U. O., … Wanwan, Z. H. U. (2014). Glacier changes in the Koshi River basin, central Himalaya, from 1976 to 2009, derived from remote-sensing imagery, 55(66), pp. 61–69. https://doi.org/10.3189/2014AoG66A057.

Douglas, J. S., Huss, M., Swift, D. A., Jones, J. M., and Salerno, F. (2016). Incorporating Distributed Debris Thickness in a Glacio-Hydrological Model : Khumbu Himalaya, Nepal, (June), pp. 1–35. https://doi.org /10.5194/tc-2016-116.

Fujii, Y., Higuchi, K., 1977. Statistical Analyses of the Forms of the Glaciers in the Khumbu Himal.

Fujii, Y., Nakawo, M., Shrestha, M.L., 1976. Mass Balance Studies of the Glaciers in Hidden valley, Mukut Himal. J. Japanese Soc. Snow Ice 38, 17–21. https://doi.org/10.5331/SEPPYO.38.SPECIAL_17.

Fujita, K., Inoue, H., Izumi, T., Yamaguchi, S., Sadakane, A., Sunako, S., Nishimura, K., Immerzeel, W.W., Shea, J.M., Kayastha, R.B., Sawagaki, T., Breashears, D.F., Yagi, H., Sakai, A., 2017. Anomalous winter-snow-amplified earthquake-induced disaster of the 2015 Langtang avalanche in Nepal. Hazards Earth Syst. Sci 17, 749–764. https://doi.org/10.5194/nhess-17-749-2017.

Fujita, K., Nakawo, M., Fujii, Y., Paudyal, P., 1997. Changes in glaciers in Hidden Valley, Mukut Himal, Nepal Himalayas, from 1974 to 1994. J. Glaciol. 43, 583–588. https://doi.org/10.3189/S002214300003519X.

Fujita, K., Nuimura, T., and Sawagaki, T. (2013). Potential flood volume of Himalayan glacial lakes and Physics Potential flood volume of Himalayan glacial lakes, (September 2014). https://doi.org/10.5194 /nhess-13-1827-2013.

Fukui K., Fujii Y., Ageta Y., Asahi K. (2006): Changes in the lower limit of mountain permafrost between 1973 and 2004 in the Khumbu Himal, the Nepal Himalayas, Global and Planetary Change doi:10.1016/j.gloplacha.2006.06.002

Grabs, W. E. and Pokhrel, A. P. (1992). Establishment of a Measuring Service for Snow and Glacier Hydrology in Nepal– Conceptual and Operational Aspects, Snow and Glacier Hydrology (Proceedings of the Kathmandu Symposium, November 1992), IAHS Publ. no. 218, 1993.

Haeberli, W., Huggel, C., Paul, F., and Zemp, M. (2013). Glacial Responses to Climate Change. (J. F. Shroder, Ed.), Treatise on Geomorphology, 13, pp. 152–175.

Haritashya, U. K., Kargel, J. S., Id, D. H. S., Leonard, G. J., Strattman, K., Watson, C. S., … Regmi, D. (2018). Evolution and Controls of Large Glacial Lakes in the Nepal Himalaya, pp. 1–31. https://doi. org/.3390/rs10050798.

Huss, M., and Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. Nature Climate Change, (January). https://doi.org/10.1038/s41558-017-0049-x.

ICIMOD, 2011. Glacial lakes and glacial lake outburst floods in Nepal. International Centre for Integrated Mountain Development, Kathmandu.

Immerzeel, W.W., Pellicciotti, F., Bierkens, M.F.P., 2013. Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. Nat. Geosci. 2013 69 6, 742–745. https://doi. org/10.1038/ngeo1896.

IPCC, 2021. SIXTH ASSESSMENT REPORT.

IPCC. (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 996. https://doi.org /10.1017/CBO9781107415324.004.

IPCC. (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. (C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, … P. M. Midgley, Eds.), A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA. https://doi.org/10.1596/978-0-8213-8845-7.

Ishikawa, M., Watanabe, T., Nakamura, N., 2001. Genetic differences of rock glaciers and the discontinuous mountain permafrost zone in Kanchanjunga Himal, Eastern Nepal. Permafr. Periglac. Process. 12, 243–253. https://doi.org/10.1002/PPP.394.

Ives, J. D., Shrestha, R. B., and Mool, P. K. (2010). Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment. ICIMOD (International Centre for Integrated Mountain Development), pp. 66.

Jianchu, X., Shrestha, A., Vaidya, R., Eriksson, M., Hewitt, K., 2007. The melting Himalayas : regional challenges and local impacts of climate change on mountain ecosystems and livelihoods 15.

Jones, D.B., Harrison, S., Anderson, K., Selley, H.L., Wood, J.L., Betts, R.A., 2018. The distribution and hydrological significance of rock glaciers in the Nepalese Himalaya. Glob. Planet. Change 160, 123–142. https://doi.org/10.1016/J.GLOPLACHA.2017.11.005.

Juen, M., Mayer, C., Lambrecht, A., Wirbel, A., Kueppers, U., 2013. Thermal properties of a supraglacial debris layer with respect to lithology and grain size. Geogr. Ann. Ser. A Phys. Geogr. 95, 197–209. https://doi.org/10.1111/geoa.12011.

Kargel, J. S., Paudel, L., Leonard, G., Regmi, D., Joshi, S., Poudel, K., Fort, M. (2013). Causes and Human Impacts of the Seti River (Nepal) Disaster of 2012, pp. 0–10.

Kargel, J.S., Leonard, G.J., Shugar, D.H., Haritashya, U.K., Bevington, A., Fielding, E.J., Fujita, K., Geertsema, M., Miles, E.S., Steiner, J., Anderson, E., Bajracharya, S., Bawden, G.W., Breashears, D.F., Byers, A., Collins, B., Dhital, M.R., Donnellan, A., Evans, T.L., Geai, M.L., Glasscoe, M.T., Green, D., Gurung, D.R., Heijenk, R., Hilborn, A., Hudnut, K., Huyck, C., Immerzeel, W.W., Jiang, L., Jibson, R., Kääb, A., Khanal, N.R., Kirschbaum, D., Kraaijenbrink, P.D.A., Lamsal, D., Liu, S., Lv, M., McKinney, D., Nahirnick, N.K., Nan, Z., Ojha, S., Olsenholler, J., Painter, T.H., Pleasants, M., Pratima, K.C., Yuan, Q.I., Raup, B.H., Regmi, D., Rounce, D.R., Sakai, A., Shangguan, D., Shea, J.M., Shrestha, A.B., Shukla, A., Stumm, D., Van Der Kooij, M., Voss, K., Wang, X., Weihs, B., Wolfe, D., Wu, L., Yao, X., Yoder, M.R., Young, N., 2016. Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake. Science (80). 351. https://doi.org/10.1126/SCIENCE.AAC8353.

Kayastha, R.B., Kayastha, R., 2020. Glacio-Hydrological Degree-Day Model (GDM) Useful for the Himalayan River Basins, in: Himalayan Weather and Climate and Their Impact on the Environment. Springer International Publishing, pp. 379–398. https://doi.org/10.1007/978-3-030-29684-1_19.

Kayastha, R.B., Steiner, N., Kayastha, R., K Mishra, S., McDonald, K., 2019. Comparative study of hydrology and icemelt in three Nepal river basins using the glacio-hydrological degree-day model (GDM) and observations from the Advance Scatterometer (ASCAT). Front. Earth Sci. 7, 354. https://doi.org /10.3389/FEART.2019.00354.

Khadka M, Kayastha RB, Kayastha R (2020). Future projection of cryospheric and hydrologic regimes in Koshi River basin, Central Himalaya, using coupled glacier dynamics and glacio-hydrological models. Journal of Glaciology 1–15. https:// doi.org/10.1017/jog.2020.51.

Khadka, N., Zhang, G., Thakuri, S., 2018. Glacial Lakes in the Nepal Himalaya: Inventory and Decadal Dynamics (1977–2017). Remote Sens. 10, 1913. https://doi.org/10.3390/rs10121913.

King, O., Bhattacharya, A., Ghuffar, S., Tait, A., Guilford, S., Elmore, A.C., Bolch, T., 2020. Six Decades of Glacier Mass Changes around Mt. Everest Are Revealed by Historical and Contemporary Images. One Earth 3, 608–620. https://doi.org/10.1016/J.ONEEAR.2020.10.019.

Kraaijenbrink, P.D.A., Bierkens, M.F.P., Lutz, A.F., Immerzeel, W.W., 2017. Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. Nature 549, 257–260. https://doi.org/10.1038/nature23878.

Linglong, M. A., Lide, T., Jianchen, P. U., and Pengling, W. (2010). Recent area and ice volume change of Kangwure Glacier in the middle of Himalayas, 55(20), pp. 12–16. https://doi.org/10.1007/s11434-010-3211-7.

Liu, X., and Chen, B. (2000). Climatic Warming in the Tibetan Plateau During, 1742, pp. 1729–1742.

Lutz, A.F., Immerzeel, W.W., Shrestha, A.B., Bierkens, M.F.P., 2014. Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. Nat. Clim. Chang. 4, 587–592. https://doi. org/10.1038/nclimate2237.

Ma, L., Tian, L., Pu, J., Wang, P., 2010. Recent area and ice volume change of Kangwure Glacier in the middle of Himalayas. Chinese Sci. Bull. 2010 5520 55, 2088–2096. https://doi.org/10.1007/S11434-010-3211-7

Maskey, S., Uhlenbrook, S., Ojha, S., 2011. An analysis of snow cover changes in the Himalayan region using MODIS snow products and in-situ temperature data. Clim. Chang. 2011 1081 108, 391–400. https://doi.org/10.1007/S10584-011-0181-Y.

MATTSON, E., L., 1993. Ablation on debris covered glaciers : an example from the Rakhiot Glacier, Punjab Himalaya. Snow Glacier Hydrol. Proc. Symp. Kathmandu 1992.

NASA, 2014. Blizzard in Nepal [WWW Document]. URL https://earthobservatory.nasa.gov/images /84585/blizzard-in-Nepal (accessed 9.12.21).

Neckel, N., Kropáček, J., Schröter, B., Scherer, D., 2015. Effects of Cyclone Hudhud captured by a high altitude Automatic Weather Station in northwestern Nepal. Weather 70, 208–210. https://doi.org /10.1002/WEA.2494.

Nepal, S. (2016). Impacts of climate change on the hydrological regime of the Koshi river basin in the Himalayan region. Journal of Hydro-Environment Research, 10, pp. 76–89. https://doi.org/10.1016 /j.jher.2015.12.001.

NGS, 2015. Everest Base Camp a 'War Zone' After Earthquake Triggers Avalanches [WWW Document]. Natl. Geogr. Soc. URL https://www.nationalgeographic.com/science/article/150425-everest-earthquake-basecamp-nepal-himalaya-climbing-sherpa (accessed 9.12.21).

Nicholson, L., Benn, D.I., 2013. Properties of natural supraglacial debris in relation to modelling sub-debris ice ablation. Earth Surf. Process. Landforms 38, 490–501. https://doi.org/10.1002/esp.3299.

Östrem, G., 1959. Ice Melting under a Thin Layer of Moraine, and the Existence of Ice Cores in Moraine Ridges. Geogr. Ann. 41, 228–230. https://doi.org/10.1080/20014422.1959.11907953.

Panday, P. K., Frey, K. E., and Ghimire, B. (2011). Detection of the timing and duration of snowmelt in the Hindu Kush-Himalaya using QuikSCAT, 2000–2008, (Mcmc), pp. 2000–2008. https://doi.org/10. 1088/1748-9326/6/2/024007.

Racoviteanu, A. E., Armstrong, R., and Williams, M. W. (2013). Evaluation of an ice ablation model to estimate the contribution of melting glacier ice to annual discharge in the Nepal Himalaya. Water Resour. Res. 49, 5117–5133. doi: 10.1002/wrcr.20370.

Radič V., Bliss, A., Beedlow, A.C., Hock, R., Miles, E., Cogley, J.G., 2013. Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models. Clim. Dyn. 2013 421 42, 37–58. https://doi.org/10.1007/S00382-013-1719-7.

Rajbhandari, R., Shrestha, A. B., and Wahid, S. (2016). Projection of Future Climate over the Koshi River Basin Based on CMIP5 GCMs, (April), pp. 190–204.

Rana, B., Shrestha, A. B., Reynolds, J. M., Aryal, R., Pokhrel, A. P., and Budhathoki, K. P. (2000). Hazard assessment of the Tsho Rolpa Glacier Lake is ongoing. Journal of Nepal Geological Society.

Richardson, S. D., and Reynolds, J. M. (2000). An overview of glacial hazards in the Himalayas. Quaternary International, 65–66, pp. 31–47. https://doi.org/10.1016/S1040-6182(99)00035-X.

Rounce, D. R., Mckinney, D. C., Lala, J. M., Byers, A. C., and Watson, C. S. (2016). A new remote hazard and risk assessment framework for glacial lakes in the Nepal Himalaya, (2013), pp. 3455–3475. https://doi.org/10.5194/hess-20-3455-2016.

Rounce, D.R., McKinney, D.C., 2014. Debris thickness of glaciers in the Everest area (Nepal Himalaya) derived from satellite imagery using a nonlinear energy balance model. Cryosph. 8, 1317–1329. https://doi.org/10.5194/tc-8-1317-2014

Salerno, F., Thakuri, S., D'Agata, C., Smiraglia, C., Manfredi, E.C., Viviano, G., Tartari, G., 2012. Glacial lake distribution in the Mount Everest region: Uncertainty of measurement and conditions of formation. Glob. Planet. Change 92–93, 30–39. https://doi.org/10.1016/j.gloplacha.2012.04.001.

Shangguan, D., Liu, S., Ding, Y., Wu, L., Deng, W., Guo, W., Wang, Y., Xu, J., Yao, X., Guo, Z., Zhu, W., 2014. Glacier changes in the Koshi River basin, central Himalaya, from 1976 to 2009, derived from remote-sensing imagery. Ann. Glaciol. 55, 61–68. https://doi.org/10.3189/2014AOG66A057.

Shea, J.M., Immerzeel, W.W., Wagnon, P., Vincent, C., Bajracharya, S., 2015. Modelling glacier change in the Everest region, Nepal Himalaya. Cryosph. 9, 1105–1128. https://doi.org/10.5194/tc-9-1105-2015.

Shean, D.E., Bhushan, S., Montesano, P., Rounce, D.R., Arendt, A., Osmanoglu, B. (2020). A Systematic, Regional Assessment of High Mountain Asia Glacier Mass Balance. Front. Earth Sci. 7. https://doi.org/ 10.3389/ FEART.2019.00363/FULL.

Shi-jin, W., and Lan-yue, Z. (2019). Integrated impacts of climate change on glacier tourism. Advances in Climate Change Research. https://doi.org/10.1016/j.accre.2019.06.006.

Shrestha, A. B., Eriksson, M., Mool, P., Ghimire, P., Mishra, B., and Khanal, N. R. (2010). Glacial lake outburst flood risk assessment of Sun Koshi basin, Nepal. Geomatics, Natural Hazards and Risk, 1(2), pp. 157–169. https://doi.org/10.1080/19475701003668968.

Shrestha, A.B., Aryal, R., 2011. Climate change in Nepal and its impact on Himalayan glaciers. Reg. Environ. Chang. 11, 65–77. https://doi.org/10.1007/s10113-010-0174-9.

Shrestha, F., Gao, X., Khanal, N.R., Maharjan, S.B., Shrestha, R.B., Wu, L., Mool, P.K., Bajracharya, S.R., 2017. Decadal glacial lake changes in the Koshi basin, central Himalaya, from 1977 to 2010, derived from Landsat satellite images. J. Mt. Sci. 14, 1969–1984. https://doi.org/10.1007/s11629-016-4230-x.

Shrestha, S., Khatiwada, M., Babel, M.S., Parajuli, K., 2014. Impact of Climate Change on River Flow and Hydropower Production in Kulekhani Hydropower Project of Nepal. Environ. Process. 2014 13 1, 231–250. https://doi.org/10.1007/S40710-014-0020-Z.

Stumm, D., Joshi, S.P., Gurung, T.R., Silwal, G., 2021. Mass balances of Yala and Rikha Samba glaciers, Nepal, from 2000 to 2017. Earth Syst. Sci. Data 13, 3791–3818. https://doi.org/10.5194/ESSD-13-3791-2021.

The Himalayan Times, 2020. Six trekkers including 4 Koreans missing in avalanche in Annapurna region [WWW Document]. URL https://thehimalayantimes.com/nepal/six-trekkers-including-4-koreans-missing-in-avalanche-in-annapurna-region (accessed 9.12.21).

Vuichard, D., and Zimmermann, M. (1987). The 1985 catastrophic drainage of a moraine-dammed lake, Khumbu Himal, Nepal : cause and consequences. Mountain Research and Development, 7(2), pp. 91–110.

Wagnon, P., Vincent, C., Arnaud, Y., Berthier, E., Vuillermoz, E., Gruber, S., Ménégoz, M., Gilbert, A., Dumont, M., Shea, J.M., Stumm, D., Pokhrel, B.K., 2013. Seasonal and annual mass balances of Mera and Pokalde glaciers (Nepal Himalaya) since 2007. Cryosphere 7, 1769–1786. https://doi.org/ 10.5194 /TC-7-1769-2013.

Watanabe, T., Khanal, N.R., Gautam, M.P., 1998. The Nangama glacial lake outburst flood occured on 23 June 1980 in the Kanchanjungha Area, eastern Nepal. Ann. Hokkaido Geogr. Soc. 13–19.

Watanabe, T., Lamsal, D., and Ives, J. D. (2009). Evaluating the growth characteristics of a glacial lake and its degree of danger of outburst flooding: Imja Glacier, Khumbu Himal, Nepal. Norsk Geografisk Tidsskrift, 63(4), pp. 255–267. https://doi.org/10.1080/00291950903368367.

Wester, P., Mishra, A., Mukherji, A., and Shrestha, A. B. (2019). The Hindu Kush Himalaya Assessment-Mountains, Climate Change, Sustainability and People. Springer Nature Switzerland AG, Cham. https://doi.org/10.1007/978-3-319-92288-1.

Williams, M.W., 2013. The Status of Glaciers in the Hindu Kush–Himalayan Region. Mt. Res. Dev. 33, 114–115. https://doi.org/10.1659/MRD.MM113.

Worni, R., Huggel, C., Clague, J. J., Schaub, Y., and Stoffel, M. (2014). Coupling glacial lake impact, dam breach, and flood processes: A modeling perspective. Geomorphology, 224, pp. 161–176. https://doi. org/10.1016/j.geomorph.2014.06.031.

Wu, B. (2005). Weakening of Indian summer Monsoon in Recent Decades. Advances in Atmospheric Sciences, 22(1), pp. 21–29.

Xiang, Y., Yao, T., Gao, Y., Zhang, G., Wang, W., and Tian, L. (2018). Retreat rates of debriscovered and debris-free glaciers in the Koshi River Basin, central Himalayas, from 1975 to 2010. Environmental Earth Sciences, 77(7), pp. 1–13. https://doi.org/10.1007/s12665-018-7457-8.

Xu, C., Sano, M., Dimri, A. P., Ramesh, R., and Nakatsuka, T. (2018). Decreasing Indian summer monsoon on the northern Indian sub-continent during the last 180 years: evidence from five treering cellulose oxygen isotope chronologies, pp. 653–664.

Xu, J., Grumbine, R. E., Shrestha, A., Eriksson, M., Yang, X., Wang, Y., and Wilkes, A. (2009). The melting Himalayas: Cascading effects of climate change on water, biodiversity, and livelihoods. Conservation Biology, 23(3), pp. 520–530. https://doi.org/10.1111/j.1523-1739.2009.01237.x.

XU, J., Grumbine, R.E., Shrestha, A., Eriksson, M., Yang, X., Wang, Y., Wilkes, A., 2009. The Melting Himalayas: Cascading Effects of Climate Change on Water, Biodiversity, and Livelihoods. Conserv. Biol. 23, 520–530. https://doi.org/10.1111/J.1523-1739.2009.01237.X.

Yamada, T., and Sharma, C. K. (1993). Glacier Lakes and Outburst Floods in the Nepal Himalaya. In Snow and Glacier Hydrology (Proceedings of the Kathmandu Symposium, November 1992) (pp. 319–330). Retrieved from http://hydrologie.org/redbooks/a218/iahs_218_0319.pdf.

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D.B., Joswiak, D., 2012. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. Nat. Clim. Chang. 2012 29 2, 663–667. https://doi.org/10.1038/ nclimate1580.

Zhang, G., Yao, T., Xie, H., Wang, W., and Yang, W. (2015). An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. Global and Planetary Change, 131(November 2018), pp. 148–157. https://doi.org/10.1016/j.gloplacha.2015.05.013.

TRANSPARENCY INTERNATIONAL NEPAL
coalition against corruption

P.O. Box: 11486
Ghar No. 57/62, Chhakkubakku Marga, New Baneshwor
Kathmandu, Nepal
Phone: 977-1-4475062, 4475262
Fax: +977-1-4475112
Toll-free tel. no.: 1660 01 22 211
Email: trans@tinepal.org
Website: www.tinepal.org
/tinepal

ISBN 978-9937-9402-5-2