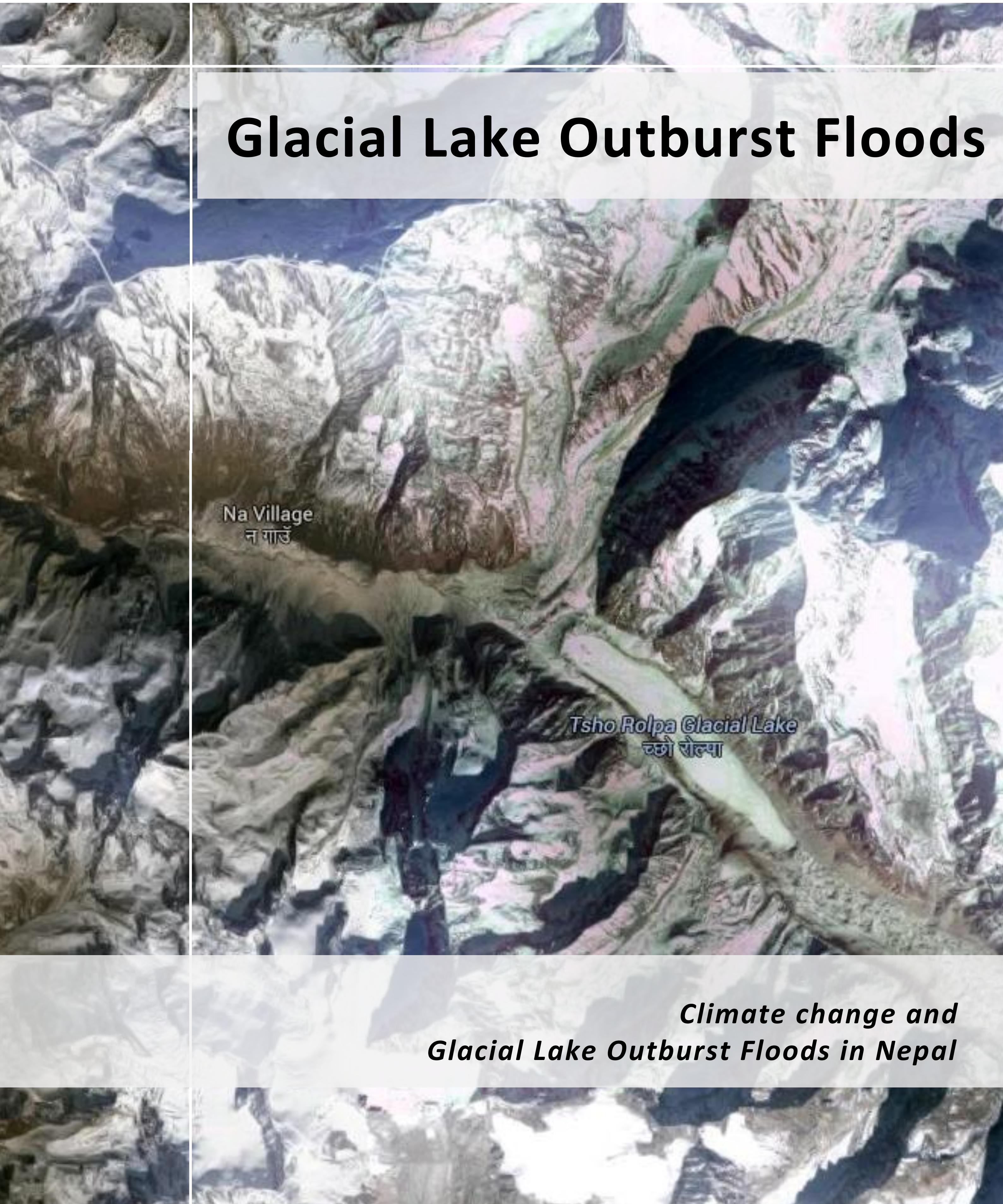
TA 7984-NEP: MAINSTREAMING CLIMATE CHANGE RISK MANAGEMENT IN DEVELOPMENT

1 Main Consultancy Package (44768-012)

Glacial Lake Outburst Floods



Climate change and
Glacial Lake Outburst Floods in Nepal

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1 INTRODUCTION

Over the past 45 years Nepal has experienced temperature rises higher than the global average. Rapidly increasing temperatures have led to melting, thinning and retreating of glaciers at an increasing pace. For example, the rate glacier retreat in east Nepal between 1815 and 1959 was 0.38 m per year and increased to 0.75m per year between 1959 and 1992. As glacier retreat has accelerated so has the size and number of glacial lakes, and the likelihood of Glacial Lake Outburst Floods (GLOFs). These high-magnitude, low-frequency floods occur when the moraine or glacier ice dam holding a glacial lake fails, suddenly releasing large amounts of water downstream.

Nepal has experienced at least 24 GLOFs in recent history, many of which caused catastrophic damage and loss of life. For example, the 1981 GLOF in Sun Koshi damaged the only road link to China and disrupted transportation and trade for several months. The 1985 Dig Tsho GLOF destroyed the nearly completed Namche Small Hydroelectric Project, and other infrastructure and dwellings further downstream.

There is global concern that climate change will lead to more GLOF events. The implications of climate change for GLOFs are of particular concern in Nepal where detailed climate modelling suggests that the region will experience significant increases in temperature and precipitation by 2050. Higher temperatures combined with increasing precipitation will lead to higher GLOF risk in Nepal as temperatures increase the rate of snow and ice melt, and high intensity rainfall increases lake water levels, slope instability and the likelihood of landslides and moraine collapse.

In this report we summarise the existing knowledge on the formation and extent of glacial lakes and GLOFs in Nepal. We then assess the implications of recent climate change modelling for GLOFs, drawing on a case study of Tsho Rolpa to illustrate the likely consequences and options for adaptation. Finally we describe the existing measures being undertaken to address GLOF risks, and provide recommendations on how these can be expanded considering the new climate change information now available.

2 GLACIAL LAKES AND GLACIAL LAKE OUTBURST FLOODS IN NEPAL

FORMATION AND EXTENT OF GLACIAL LAKES IN NEPAL

In the Middle Mountain and Himalayan regions of Nepal temperature rises during the last 45 years have been higher than the global average. Analyses of maximum temperature data from 49 stations in Nepal for the period 1971–94 reveals warming trends after 1977 of up to 0.128 ^{o}C/yr (Shrestha et.al., 1999). Another study based on data from 1975 to 2005 showed that the mean temperature of Nepal is increasing at a rate of 0.04°C/year, with the warming more pronounced in higher altitude regions in the Middle Mountains and Himalayas (Baidya et. al., 2007).

Increasing temperatures in the Middle Mountain and Himalayan regions has led to melting, thinning and retreating of glaciers (ICIMOD, 2011; Fujita and others, 2001). There is now clear evidence that the retreat of glaciers across the globe has accelerated in recent decades (Zemp et al. 2008) and studies show that Nepal's glaciers are retreating faster than the world average (Dyurgerov and Meier, 2005). For example, the rate of glacier retreat in east Nepal (Kanchanjunga, Khumbu, Rolawaling and Langtang) was 0.38 m per year between 1815 and 1959 and increased to 0.75m per year between 1959 and 1992 (Kayastha and Harrison, 2008).

As glacier retreat has accelerated so has the size and number of glacial lakes. Glacial lakes form when a retreating glacier leaves behind a debris mass at the end of the glacier, called the end moraine, which acts as a natural dam, trapping water from the glacier and forming a lake (Horstmann, 2004; ICIMOD, 2010). As glaciers thin and retreat these meltwater lakes – predominantly supraglacial[1] and moraine dammed[2] - are increasing in size and number (ICIMOD, 2011; Bajracharya and Mool, 2009). Systematic application of remote sensing and air photo interpretation has shown that, in recent years, many hundreds of glacial lakes have formed while others have enlarged, sometimes exceeding lengths of two kilometres and with depths approaching a hundred metres (ICIMOD, 2011). A 2011 study by ICIMOD identified 3,808 glaciers and 1,466 glacial lakes in Nepal out of which 21 are identified as potentially dangerous (ICIMOD, 2011).

The size of glacial lakes in Nepal is increasing. For example, Imja Glacial Lake in Solukhumbu district increased from only a few small ponds in 1960, to 1.01 sq.km in 2009. Similarly, Tsho Rolpa Glacial Lake in Dolakha district increased in size from 0.23 sq. km in 1958 to 1.54 sq. km. in 2009. Finally, Thulagi Glacial Lake in Gorkha district increased its size from 0.22 sq. km. in 1958 to 0.94 sq. km. in 2009. Many other glacial lakes across Nepal have seen similar increases in size.

GLACIAL LAKE OUTBURST FLOODS IN NEPAL

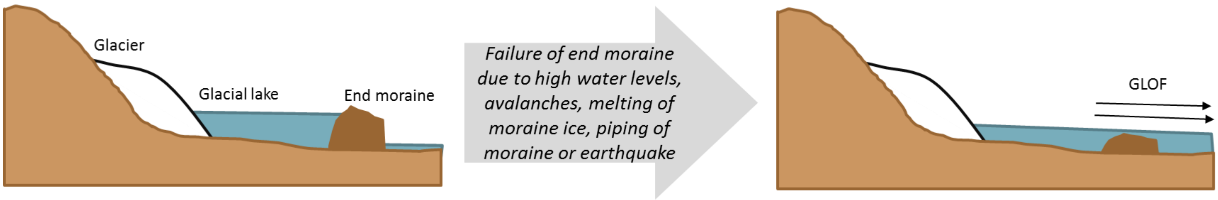
Glacial Lake Outburst Floods (GLOFs) are high-magnitude, low-frequency catastrophic floods that occur when the moraine or glacier ice dam holding a glacial lake fails, releasing large amounts of water downstream with often catastrophic results (Bajracharya and Mool, 2009). The moraine dams are composed of unconsolidated boulders, gravel, sand and silt, and therefore are not structurally sound and prone to failure. Dam failures occur as the glacial lakes increase in size, increasing the potential energy of the water volume and breaching the often weak and loose moraine or ice dam (Figure 1). GLOFs can be triggered by several factors including: i) increasing water levels putting more pressure on the moraine dams; ii) ice or rock avalanches causing waves within the lake that put pressure on the moraine dams; iii) melting of ice buried within the moraine dam that reduces its structural integrity; iv) piping of the moraine dam (i.e. washing out of fine materials from the moraine) that reduces its

[1] Supraglacial lakes are any pond of liquid water on the top of a glacier.

[2] A lake formed as a glacier recedes from its terminal moraine, the moraine acting as an unstable dam

structural integrity; or iv) earthquakes or sudden inputs of water into the lake from heavy rains upstream.

Figure 1. Formation of glacial lakes and GLOFs



The likelihood of a GLOF occurring depends on the characteristics of a lake, its dam and associated glaciers (Mool et al. 2001a). Characteristics include the lake size; the rate at which the lake is expanding; lake position with respect to the mother glacier; height of the moraine dam; overtopping height (free board); origin of the lake (supra, cirque, moraine dammed); the existence of hanging glaciers or potential rock and debris fall or slides; and the volume of lake water.

A number of GLOFs have been reported in Nepal in the last few decades, particularly in the eastern region (Mool et al, 2001b; Yamada, 1998; Richardson & Reynolds, 2000). Altogether Nepal has experienced at least 24 GLOF events (Figure 2). Of these, 14 are believed to have occurred in Nepal itself (Table 1), and 10 were the result of flood surge overspills across the China-Nepal border (ICIMOD, 2011). Of the 14 GLOF events known to have occurred in Nepal, one took place around 450 years ago, seven took place in the last thirty years, and six took place at an unknown time (ICIMOD, 2011). Recent studies have identified another 21 potentially critical glacial lakes that are prone to burst (ICIMOD, 2010; ICIMOD, 2011).

Figure 2. Location of GLOF events recorded in Nepal, or occurring in Tibet with effects in Nepal (ICIMOD, 2011)

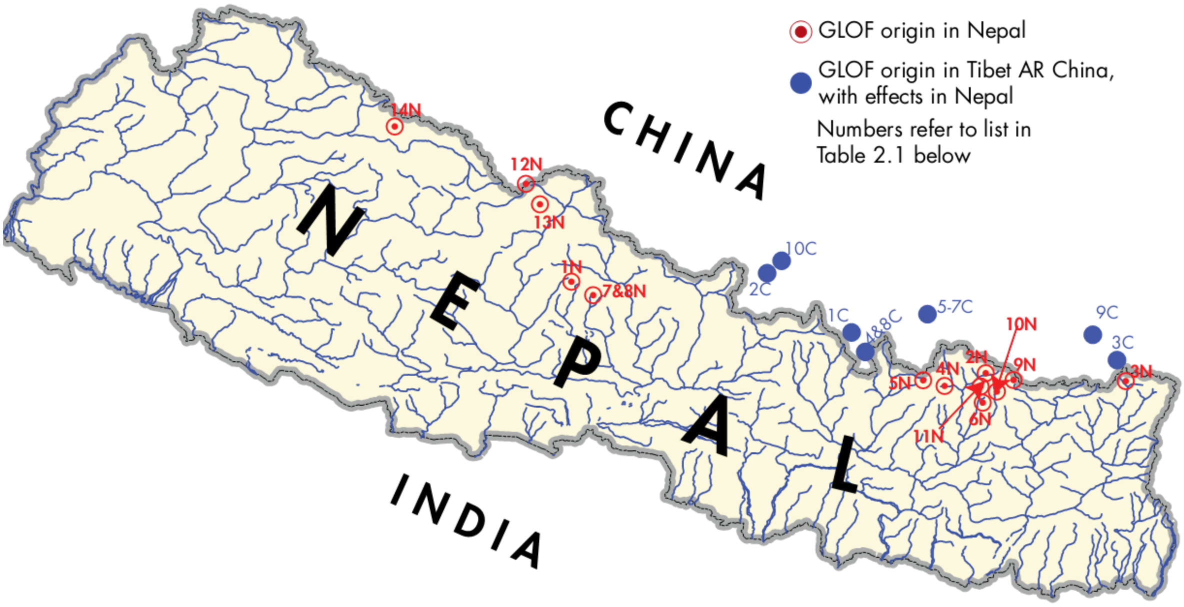


Table 1 GLOF events recorded in Nepal (after Mool et al., 1995, 2001b; Yamada, 1998; Bajracharya et al., 2008; Ives et al., 2010).

No.	Date	River basin	Lake	Cause	Losses
1	450 years ago	Seti Khola	Machhapuchhre	Moraine collapse	Pokhara valley covered by 50–60m deep debris
2	3 Sep 1977	Dudh Koshi	Nare	Moraine collapse	Human lives, bridges, others
3	23 Jun 1980	Tamor	Nagma Pokhari	Moraine collapse	Villages destroyed 71 km from source
4	4 Aug 1985	Dudh Koshi	Dig Tsho	Ice avalanche	Human lives, hydropower station, 14 bridges, etc
5	12 Jul 1991	Tama Koshi	Chubung	Moraine collapse	Houses, farmland, etc
6	3 Sep 1998	Dudh Koshi	Tam Pokhari	Ice avalanche	Human lives and more than NRs 156 million
7	15 Aug 2003	Madi River	Kabache Lake	Moraine collapse	Not known
8	8 Aug 2004	Madi River	Kabache Lake	Moraine collapse	Not known
9	Unknown	Arun	BarunKhola	Moraine collapse	Not known
10	Unknown	Arun	BarunKhola	Moraine collapse	Not known
11	Unknown	Dudh Koshi	Chokarma Cho	Moraine collapse	Not known
12	Unknown	Kali Gandaki	Unnamed (Mustang)	Moraine collapse	Not known
13	Unknown	Kali Gandaki	Unnamed (Mustang)	Moraine collapse	Not known
14	Unknown	Mugu Karnali	Unnamed (Mugu Karnali)	Moraine collapse	Not known

3 IMPLICATIONS OF CLIMATE CHANGE FOR GLACIAL LAKE OUTBURST FLOODS IN NEPAL

IMPLICATIONS OF CLIMATE CHANGE FOR GLOFS IN NEPAL

There is global concern that climate change will lead to more GLOF events. As temperatures rise, glaciers will recede faster, increasing the volume of water being released downstream. This water may be stored in glacial lakes and studies have shown that the rate of glacial lake extension is directly proportional to glacier retreat (ICIMOD, 2010). Increasing glacial lake sizes, along with increasing numbers of glacial lakes, will lead to higher risk of GLOF events as more pressure is put on the fragile moraine dams. Increasing rainfall with climate change will also make GLOFs more likely by expanding lake volumes and causing greater slope and moraine instability.

The implications of climate change for GLOFs are of particular concern in the high Himalaya districts of Mustang and Dolakha. Detailed climate and hydrological modelling suggests that these districts will experience major increases in temperature and precipitation by 2050 including (MoSTE, 2014a; MoSTE 2014b):

- An increase in the days of the year where the maximum temperature exceeds 0^{o}C from 50 to 70 days in high elevation areas of Dolakha District;
- An increase in the days of the year where the maximum temperature exceeds 0^{o}C from 60 to 65 days in high elevation areas of Mustang District;
- An increase in the average maximum temperature in the dry season of up to 3.5 ^{o}C in the higher elevations of Dolakha District;
- An increase in average maximum temperatures in the wet season of up to 1.7 ^{o}C in high elevations of Mustang District;
- An increase in wet season mean monthly precipitation by up to 180mm in high elevation areas of Dolakha District; and
- Increase in total wet season precipitation by up to 50mm a year in Mustang District.

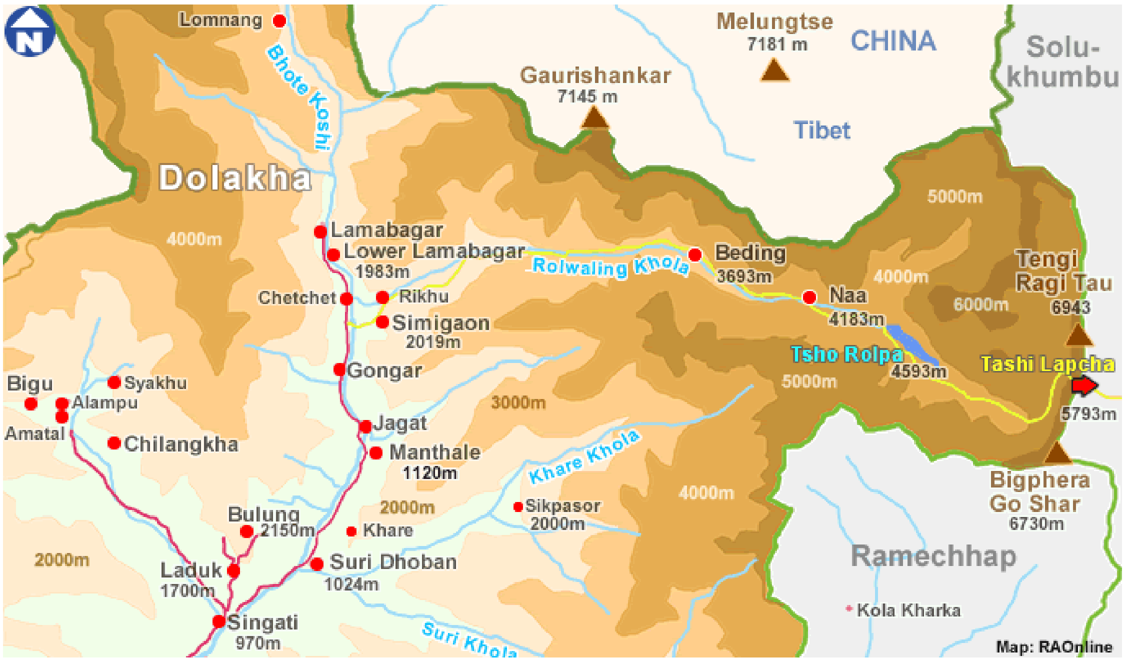
Annex A provides more details of projected changes in climate for Mustang and Dolakha Districts. Higher temperatures combined with increasing rainfall in both the dry and wet season will lead to higher GLOF risk - temperature increases promote snow and ice melt, and increases in rainfall volume and intensity raises lake water levels and the likelihood of landslides into lakes.

TSHO ROLPA GLACIAL LAKE CASE STUDY

Background and baseline of Tsho Rolpa Glacial Lake

Tsho Rolpa Glacial Lake, Nepal’s largest glacial lake, is located in the Rolwaling Valley, Dolakha District, in the central Nepal Himalayas (Figure 3). The lake is at the terminal of the Trakarding Glacier at an altitude of 4,546 masl and forms the headwaters of Rolwaling Khola, a tributary of the Tama Koshi River. In recent decades, Tsho Rolpa lake has been expanding rapidly. The Survey of India performed a topographic survey of the lake in 1958 and recorded a surface areas of 0.23 km2. By 1999 the surface area had increased to 1.55 km2 (ICIMOD, 2011). The historical trend and future projections of continuing changes at Tsho Rolpa has made Dolakha one of the most GLOF vulnerable districts in Nepal and has serious implications for downstream areas. At least 3 large hydropower plants and a number of micro-hydropower installations could be washed away in the event of a glacial flood.

Figure 3 Tsho Rolpa Glacial Lake in Dolakha District Nepal



Source: http://www.raonline.ch/images/np/maps/np_RolwalingMap01.gif

In 1998, an early warning system was installed for Tsho Rolpa with 11 warning stations located progressively downstream for 106 km. After a few years the system ceased to function. In 1999, the Government identified Tsho Rolpa as the glacial lake in the country most at risk of bursting. In 2000, engineering works were undertaken to install a drainage canal to lower the lake water level by 3 m. With that infrastructure in place, the lake area appears to have stabilised at around 1.45 km^2 with 76.6 million cubic meters of stored water.

For the purposes of vulnerability assessment, the Tsho Rolpa system can be divided into four main components – each with distinctive characteristics and sensitivities:

1. **Mother glacier and feeder stream:** Trakarding Glacier is the mother glacier of Tsho Rolpa Glacial Lake (Figure 4). The glacier is about 17 km long, and is highly fractured and debris covered. In 1995, its front ice wall was around 45m high, but by 2009, the height had reduced to 10 m due to extensive melting and retreat.
2. **The lake:** The largest glacial lake in Nepal with an area of 1.45 km^2 (Figure 5)
3. **Lateral Moraines**: The lateral moraines of Tsho Rolpa Glacial Lake (Figure 6) are about 50 m high with slope of more than 45^o in most sections. The moraines are mainly loose silt, sand, boulder and rock.
4. **End moraine, open canal and gate**: The end moraine is 130 m high and comprised of loose gravel and boulders (Figure 7). In 2000, an open canal was constructed through the end moraine to drain water from the lake. The canal is 70 m long, has a 6.2 m top width and can drain up to 30 m^3/s of water (Figure 8). The canal is fitted with an iron gate to control discharges.

Figure 4. Mother glacier of Tsho Rolpa Glacial Lake

Figure 5. Plan view of Tsho Rolpa

Figure 6. Lateral moraine of Tsho Rolpa Glacial Lake

Figure 7. End moraine of Tsho Rolpa Glacial Lake in Dolakha district, Nepal.

Figure 8. Open canal of Tsho Rolpa Glacial Lake, and iron gate on the open canal

Climate change threats to Tsho Rolpa

The Ministry of Population and Environment's Department of Hydrology and Meteorology, with support from ICEM, has prepared climate threat profiles for Dolakha and seven other districts using localised projections of future climate change for 2050 compared to baseline data for 2000. Statistical downscaling for several temperature and precipitation stations were used to develop these projections.[3] The results of the downscaling were incorporated into a basin-wide hydrological model to compute projected changes in temperature, precipitation, river discharge and runoff within each district.

The climate threat modelling shows that Dolakha District is projected to undergo major changes in climate by 2050 (MoSTE 2014a). The threats most likely to impact the Tsho Rolpa Lake and Trakarding Glacier include (more detail is provided Annex A):

- **Increasing precipitation**
    - There will be more rainfall occurring upstream of the lake and on the glacier and surrounding slopes. For example, at the Tsho Golpa site wet season mean monthly precipitation will increase by 100 mm (Figure 10);
    - Large and intensive rainfall events will occur more often. For example, by 2050, a 250 mm rainfall event which previously occurred every 100 years, will occur every 40 years, more than twice as often; and
    - Rainfall intensities will increase by 84 %.
- **Increasing temperatures**
    - Maximum temperatures will increase. For example, at Tsho Rolpa Lake the average maximum temperature is projected to increase by up to 1.5 ^{0}C (Figure 9); and
    - Higher temperatures will occur more frequently and the duration of high temperatures will be longer. For example, the number of days per year over 15^{0}C will increase from 25 to 50 days per year.
- **Increasing risk of landslides**

[3] Nine meteorological stations and two discharge stations were used for the Dolakha District model

- The average erosion rate will increase by up to 7.2 kg/m^2 b/year between 2000 and 2050. Erosion with increased thawing and ground saturation means that landslides in the vicinity of the lake will occur on a larger scale and more frequently (Figure 11)

Figure 9. Projected increase in average maximum temperatures in Dolakha District between 2000 to 2050

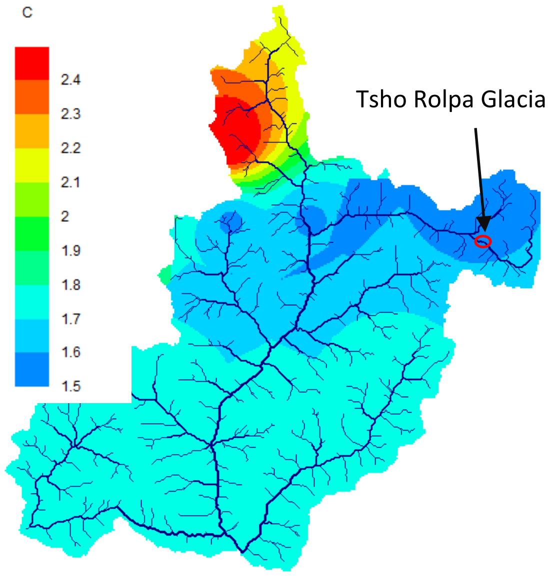


Figure 10. Projected increase in wet season mean monthly precipitation in Dolakha District between 2000 to 2050

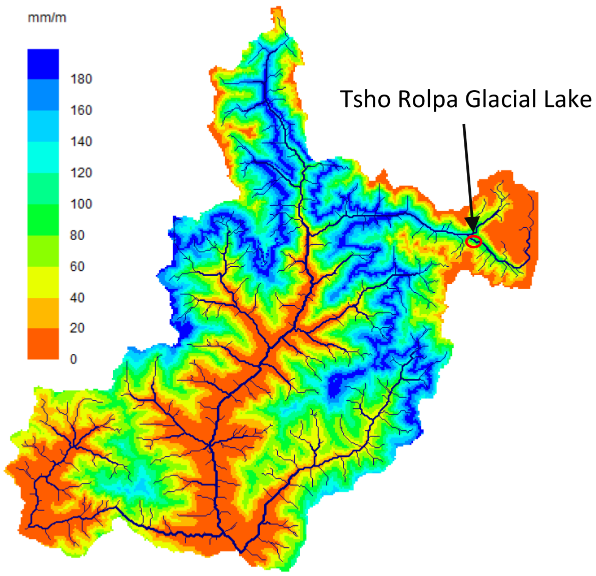
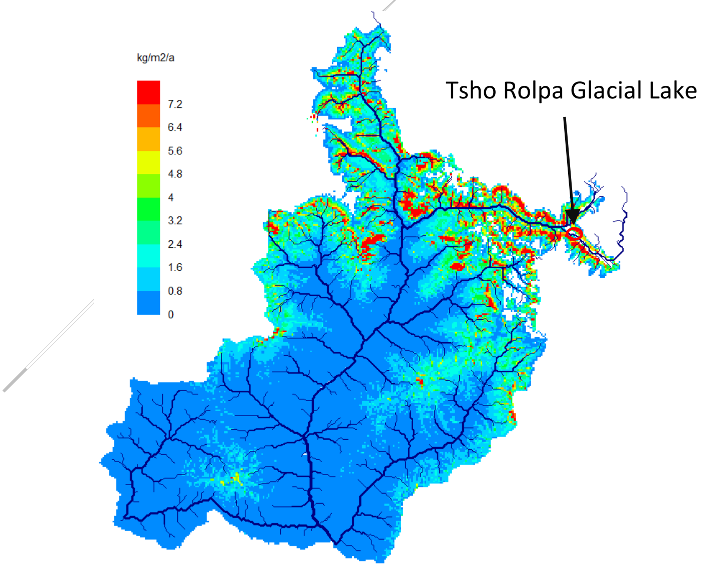


Figure 11 Change in average annual erosion rate (kg/m2/a) for Dolakha District between 2000 and 2050



Vulnerability assessment for Tsho Rolpa Lake

A vulnerability assessment of the main components of the Tsho Rolpa Glacial lake system was undertaken to understand the implications of changing climate for the risks of an GLOF. The main climate change threats identified for Tsho Rolpa Glacial Lake are increasing rainfall and temperatures that may lead to increasing rates of glacier retreat and water levels, thus increasing the likelihood of a GLOF. The vulnerability assessment methodology[4] considered each component's exposure[5] and sensitivity[6] to the identified climate change threats to understand the potential impacts.[7] Then a vulnerability ranking was determined by incorporating a measure of the adaptive capacity[8] of each component and the managing agencies. The ranking enables analysis of which glacial lake components are the most vulnerable to climate change and therefore require priority adaptation attention to build resilience in the system overall (Table 2).

Table 2 Climate change impacts and vulnerability for Tsho Rolpa Glacial Lake

System component	CC Threat	Impact	Vulnerability
Lake	Increase in rainfall	Increasing inflow of water into the lake leading to higher water levels and more pressure on the end and lateral moraines and potential collapse or breach	Very High
	Increase in temperature	Increasing snow and ice melt leading to higher water levels and more pressure on the end and lateral moraines and potential collapse or breach	Very High
End moraine or outlet	Increase in rainfall	Increasing intensity and total rainfall will increase the moisture content of the end moraine making it more prone to failure	Medium
	Increase in temperature	Increasing temperatures may melt ice and frozen material within the end moraine, thus reducing its structural integrity increasing likelihood of failure	Medium
Lateral moraines	Increase in rainfall	Increasing rainfall will increase the moisture content of the lateral moraines thus increasing the likelihood of landslides leading to catastrophic increase in lake water levels and breach of end moraine	Low to medium
	Increase in Temperature	Melting of frozen material within the moraine increasing likelihood of collapse	Low to medium
Mother glacier and feeder streams	Increase in rainfall	Increased rate of snow and ice melt leading to higher water levels in the lake and more pressure on the end and lateral moraines	Very High
	Increase in Temperature		Very High

[4] See MoSTE (2014c) for a detailed description of the vulnerability assessment methodology
[5] **Exposure** is the extent to which a system is exposed to the climate change threat.
[6] **Sensitivity** is the degree to which a system will be affected by, or responsive to the exposure.
[7] The potential **impact** is a function of the level of **exposure** to climate change threats, and the **sensitivity** of the target assets or system to that exposure.
[8] **Adaptive capacity** is defined as the ability of a system to adjust to climate change to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

Adaptation planning for Tsho Rolpa

The Tsho Rolpa Glacial Lake and Trakarding Glacier have been identified as highly vulnerable to increasing temperature and rainfall increasing the lake water levels and placing more pressure on the end and lateral moraines (Table 1). Therefore the adaptation measures identified below focus on minimizing the risk of GLOF by reducing the volume of water in the lake and strengthening the moraine dam.

Lowering the level of the lake

The lake water level can be lowered using one of two techniques:

- **Siphons**: PVC pipes can be used to install siphons which will take out lake water without mechanical devices. Generally, small pipes (6 inch) are used in siphons and can only drain a minimal volume of water. A test siphon installed in 1995 only discharges 177 l/s from the lake which is not sufficient when compared to the lake inflow; and
- **Constructing open canal outlet by cutting the end moraine:** An open channel outlet can be constructed by cutting the end moraine part of the lake. The dimension of the channel can be calculated so that desired level of water is achieved. Tsho Rolpa has an existing moraine channel which is 6.2 m top wide and 70 m long with a capacity of 30 m^3/s discharge.

Removing or lowering the external risks to the lake

If there are any external risks such as hanging glaciers, landslides or rock falls these should be removed or the likelihood of them occurring reduced. This could be completed by careful removal of the ice or rock, or protection works such as cementing or gabions that will reduce the possibility that falling glaciers or rocks will directly enter the lake.

Strengthening the end moraine

Strengthening of the end moraine reduces the risk of moraine failure. Strengthening can be undertaken using cement grouting of the end moraine or constructing gabion wire boxes filled with stones to support the moraine. Cement concreting or gabion wire boxes with stone can also be used to increase the free board of the existing outlet of the lake which will reduce scouring effects of outflows.

Installation of Early Warning System

Early warning systems are intended to provide timely and effective warning of an impending GLOF to allow downstream communities to take action to avoid or reduce possible impacts. In 1998, an early warning system for Tsho Rolpa was set up by the Department of Hydrology and Meteorology (DHM). After several years, it ceased to function because of limited financing, maintenance and political conflicts. In 2015, following the powerful earthquake and aftershocks, a DHM team supported by UNDP installed another early warning system for Tsho Rolpa using two sensors, one for monitoring water level and another for water content of the end moraine (ReliefWeb, 2015). The earthquake did not appear to have destabilized the lake system but the increasing seismic activity in the area brought a heightened sense of urgency to reestablish an effective EWS.

CASE STUDY CONCLUSIONS

Nepal has 1,466 glacial lakes. Tsho Rolpa Lake is Nepal's largest glacial lake and one of the 21 most at risk of an outburst flood (i.e. a GLOF). The vulnerability assessment and adaptation planning undertaken for Tsho Rolpa Lake and summarized in this report found that projected climate changes for Dolakha District will significantly increase the likelihood of a Tsho Rolpa Lake outburst. By 2050, wet season average monthly rainfall is projected to increase by 100mm, with rainfall intensities up by 84% and events of over 250mm occurring more than twice as often. Maximum temperatures are projected to increase by 1.5^{0}C with a doubling to 50 the number of days per year over 15^{0}C. The effects of most concern are increasing water volume flowing into the lake from glacier and snow melt and more intense rainfall events leading to incremental and sudden increases in water levels. The likelihood and severity of impacts can be greatly reduced by taking a number of relatively straight forward adaptation interventions. Those measures include deepening and widening the existing outflow channel in the end moraine to achieve a stable calculated water level in the lake, reinforcing the channel walls (weakened during the recent Gorkha Earthquake) to reduce erosion from the outflow, and strengthening the moraine.

4 ADDRESSING CLIMATE CHANGE IMPACTS ON GLACIAL LAKE OUTBURST FLOODS IN NEPAL

EXISTING RESPONSES TO GLACIAL LAKE OUTBURST FLOODS IN NEPAL

Strategic planning

In 2010 the Government of Nepal released its National Adaptation Programme of Action for climate change (NAPA). The NAPA prioritizes GLOF risk reduction and proposes a number of activities including monitoring of glacial lakes, developing early warning systems, enhancing institutional capacity, assessing hazards, developing contingency plans, and initiating GLOF research and development (Khanal et al, 2015). In 2011 the government endorsed a national framework for Local Adaptation Plans of Action (LAPA) which provides guidelines for formulating and implementing GLOF planning at the local level with an integrated approach.

Inventory, research and monitoring

Nepal has made good progress in glacial lake inventory, GLOF risk identification and assessment, monitoring and early warning systems (Mool et al 2001, ICIMOD, 2011). GLOFs in Nepal were not studied in detail until 1981 when two major GLOF events prompted action. The Water and Energy Commission Secretariat (WECS) then began an investigation of the potential threat of GLOFs that included the first attempt to inventory glacial lakes in Nepal. This early report laid the groundwork for intensive research on GLOFs culminating in a large ICIMOD study that undertook an inventory of glacial lakes across Nepal using remote sensing, categorised the glacial lakes according to the risk of a GLOF occurring, identified three particularly at-risk lakes and undertook detailed risk assessments of these lakes (ICIMOD, 2010; ICIMOD, 2011). Following this intensive period of research, many lakes, including those most at risk, need to be continually monitored.

Early warning systems

Early warning systems are intended to provide timely and effective warning of an impending GLOF to allow downstream communities to take action to avoid or reduce possible impacts. In Nepal, early warning systems have been installed at various locations including Tsho Rolpa, Upper Bhote Koshi valley and Imja Tsho. These early warning systems have had mixed success, with long term sustainable support and funding being the main challenge for continued operation of the systems.

Mitigation works

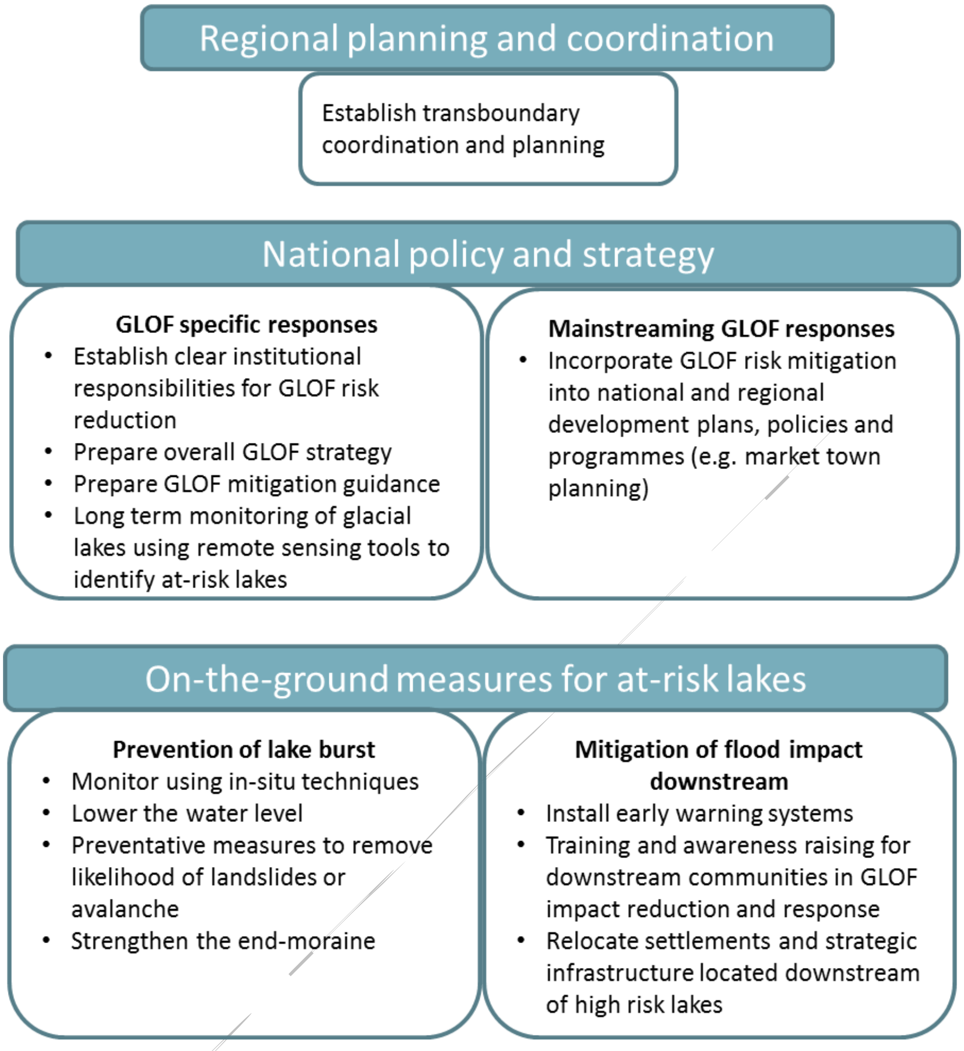
GLOF mitigation works are physical works undertaken to reduce the volume of water in a glacial lake, thus reducing water levels, the likelihood of moraine failure and the peak discharge in a GLOF event should one occur. Mitigation measures such as removal of loose rocks or snow/ice that may fall into the lake also reduce the likelihood of sudden pressure on the end moraine dam.

Structural mitigation works for GLOF risk reduction are effective but expensive, and therefore cannot be applied to all the glacial lakes in Nepal identified as high GLOF risk (ICIMOD, 2011). In Nepal GLOF mitigation works have only been undertaken at a small number of sites with the mitigation works for Tsho Rolpa Lake discussed in Chapter 2 being the most substantial. In most cases structural mitigation works will not be possible and other, less expensive, responses, such as early warning systems, need to be put in place.

RECOMMENDATIONS

Nepal is responding to the risk of GLOFs, yet the analysis presented in this report shows that with projected changes climate, GLOFs are likely to become more common, and Nepal's response needs to be better coordinated and strengthened. Nepal's response to the increasing risk of GLOFs due to climate change needs to take place at three levels: i) regional planning and coordination; ii) national policy and strategy; iii) and on-the-ground prevention and mitigation (Figure 12).

Figure 12 Three levels of response to the increasing risk of GLOFs in Nepal



At the regional level, the establishment of coordination and planning mechanisms between the South Asian countries affected by GLOFs – Nepal, Bhutan, Pakistan, India and China - would enable sharing of new knowledge on GLOF risk and mitigation, and improve transboundary responses to GLOFs. For example, at least 10 of the recent GLOF events impacting Nepal were the result of flood surge overspills across the China-Nepal border. Transboundary coordination is needed to ensure that Nepal is updated on the risk of a GLOF occurring and crossing the border, and that Early Warning Systems and planned responses are harmonised between the two countries.

At the national level, policies and strategies need to be put in place to establish responses to the GLOF risk and to mainstream consideration of GLOFs into government planning. This could include:

- **Establishing clear responsibilities for GLOF risk reduction**: Currently there is no clear institutional responsibility for GLOF monitoring and management and many governmental and non-governmental organisations are involved. A single organisation, such as the Department of Hydrology and Meteorology (DHM), needs to be given the mandate and budget to take the lead in all GLOF related preventative and resilience building measures. DHM is an appropriate agency as they have taken the lead on existing GLOF related projects such as the UNDP funded Community Based Flood and Glacial Lake Outburst Risk Reduction Project. DHM's institutional capacity should be enhanced to ensure sufficient human and financial resources to carry out glacial lakes and GLOF related activities across Nepal.

- **Prepare overall GLOF strategy**: There is no overall strategy for Nepal to address GLOFs and therefore current responses are taken on an ad-hoc basis. An overall GLOF strategy needs to be prepared and endorsed by all levels of government. This strategy would summarise the current GLOF situation in Nepal and the likely impacts of climate change on GLOFs, then outline the government's coordinated responses including prioritisation, responsibility and funding.
- **Prepare GLOF mitigation guidance**: There is currently no guidance and design standard prepared for GLOF prevention and mitigation works in Nepal. The development of GLOF prevention and mitigation guidance would streamline the design process and ensure consistent application of best practice techniques. The guidance may include suggestions on best practice approaches appropriate in the Nepal context for in-situ monitoring, glacial lake water level lowering, moraine strengthening and reducing landslide and avalanche risk around glacial lakes.
- **Long term monitoring and identification of lakes at risk of outburst**: The formation and growth of glacial lakes can change rapidly over time, therefore a long term national level monitoring program needs to be put in place to track the development of glacial lakes and identify at-risk lakes. Remote sensing techniques could be used to monitor lake and glacier sizes, as well as other important characteristics such as the location of downstream communities. The ICIMOD 2011 study, along with early studies, has established a comprehensive baseline of the glacial lake situation, and long term government commitment is needed to ensure that monitoring continues into the future.
- **Incorporate GLOF risk mitigation into national and regional development plans, policies and programmes:** Consideration and responses to GLOFs needs to be incorporated into Government of Nepal national and regional development plans, policies and programmes. For example, market town planning should avoid development of markets in areas identified as GLOF-prone, and strategic road infrastructure should be located away from GLOF-prone areas.

For glacial lakes identified as at-risk of a GLOF event, on-the-ground measures should be taken to prevent lake outbursts and mitigate the potential impact of floods downstream. Measures to prevent a GLOF event may include:

- **In-situ monitoring**: In-situ monitoring of lake water levels and end-moraine stability for at-risk glacial lakes would allow for early identification of the conditions that may lead to a GLOF, allowing for emergency works to be undertaken to reduce the likelihood of a GLOF event. This monitoring could also inform an early warning system to alert downstream communities.
- **Lowering the lake water level**: The most common physical response for at-risk lakes is to reduce the lake water level thus decreasing the pressure on the end moraine and the potential flood peak. The lake water level can be reduced through a number of techniques including i) controlled breaching of the moraine dam; ii) construction of outlet control structures such as those established at Tsho Rolpa; iii) pumping or siphoning of water from the lake, as was attempted at the Tsho Rolpa; or iv) tunnelling through the moraine dam.

- **Preventative measures around the lake**: Preventative measures around the lake can be taken to reduce the likelihood of a landslide or avalanche entering the lake and causing a wave that may destabilise the end moraine. These measures include the removal of masses of unstable rocks, concreting of unstable slopes or construction of barriers.
- **Strengthening of the end moraine**: Concreting or gabion walls can be used to strengthen the end moraine and reduce the likelihood of failure.

Measures to mitigate the impact of floods downstream of an at-risk glacial lake may include:

- **Install early warning systems**: Installation of an Early Warning System (EWS) is an important adaptation measure to avoid loss of life and reduce damage in the event of a lake outburst. The objective of a combined community and high tech based EWS is to provide a safe, secure, reliable warning system to the downstream villages and infrastructure managers in as short a time as possible. The system should include water level measurement and warning stations at the lake with communications links to downstream locations. For example, sensors may be inserted into the moraine dam that detect movement and can identify when the dam may be about to break, the sensors then trigger a mass communication system which communicates the possible GLOF threat to downstream communities. These systems needs to be technically sound, simple to operate, easy to maintain and reliable (ICIMOD, 2011).
- **Training and awareness raising**: It is important to raise the awareness of downstream communities and local government bodies on the formation of glacial lakes, their characteristics, levels of GLOF risk, and appropriate actions to take during and after GLOF events.
- **Relocate settlements and strategic infrastructure**: Downstream of sites of major GLOF risk, relocation of existing settlements and/or strategic infrastructure may be required. Due to the high costs of this measure it should only be undertaken in the case of potentially catastrophic impacts.

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ANNEX A: CLIMATE CHANGE PROJECTIONS FOR MUSTANG AND DOLAKHA DISTRICTS

MUSTANG DISTRICT

Figure 13 Projected change in average maximum temperature in the wet season for Mustang District

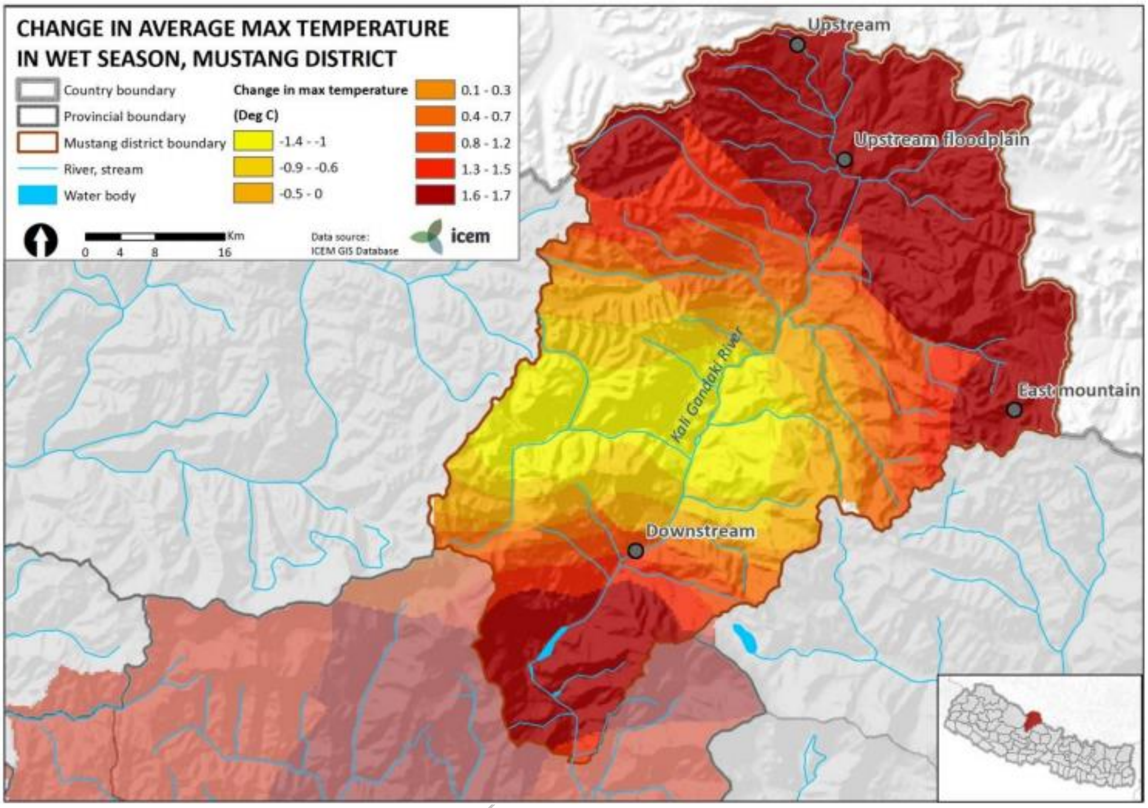


Figure 14 Projected change in temperature exceedance probabilities for high elevation areas of Mustang district

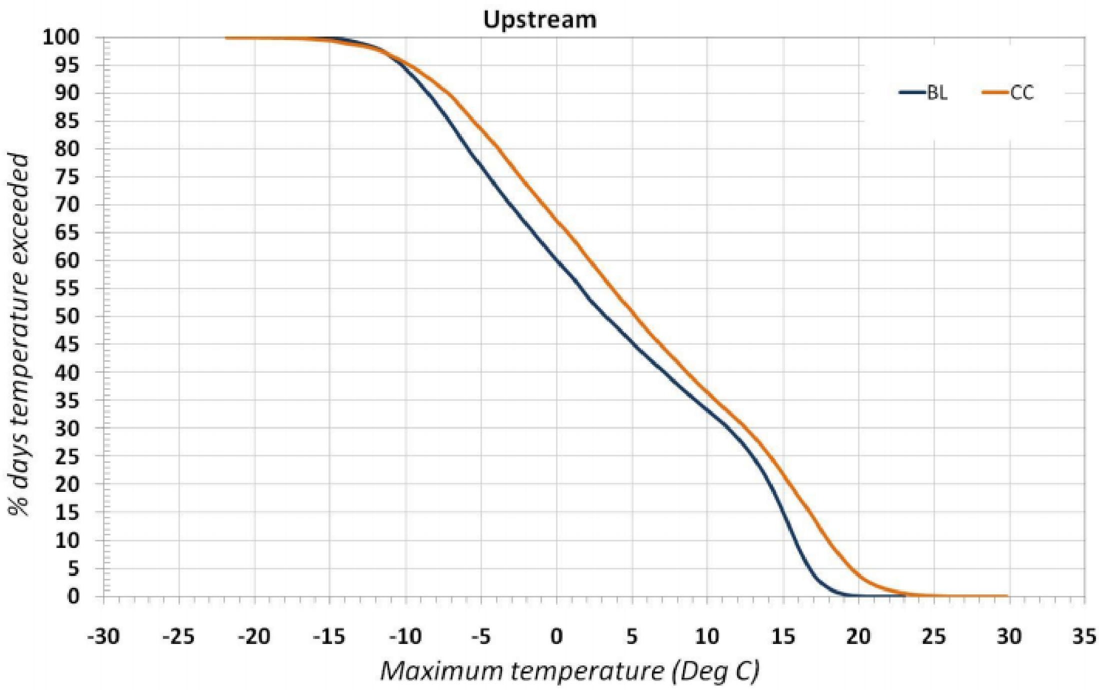
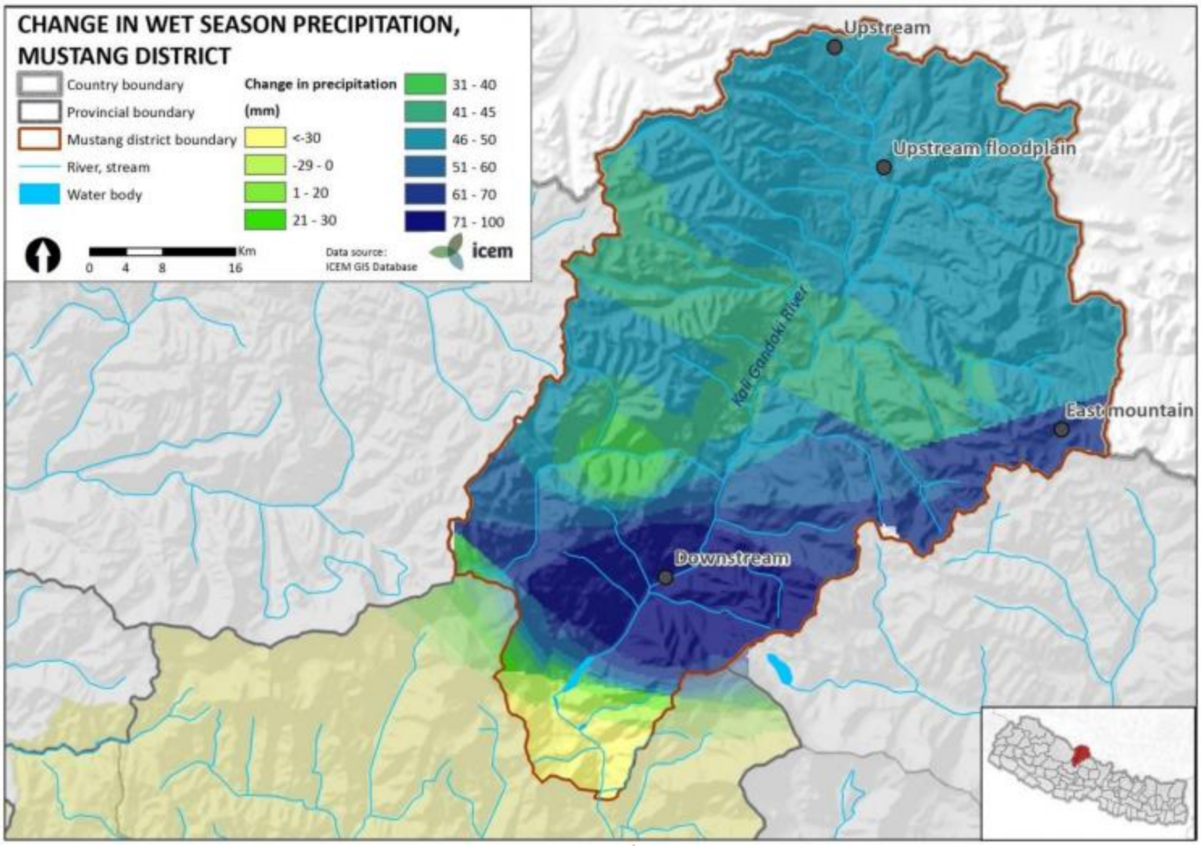


Figure 15 Projected change in total wet season precipitation in Mustang District



DOLAKHA DISTRICT

Figure 16 Change in average maximum temperature in the dry season for Dolakha District

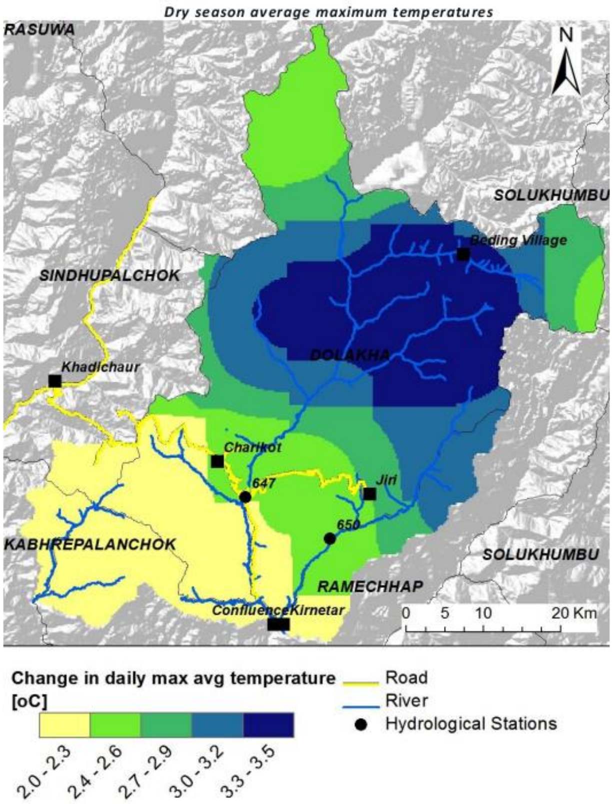


Figure 17 Projected change in temperature exceedance probabilities at Bedding Village of Dolakha district (just downstream, of the Tsho Rolpa Glacial Lake)

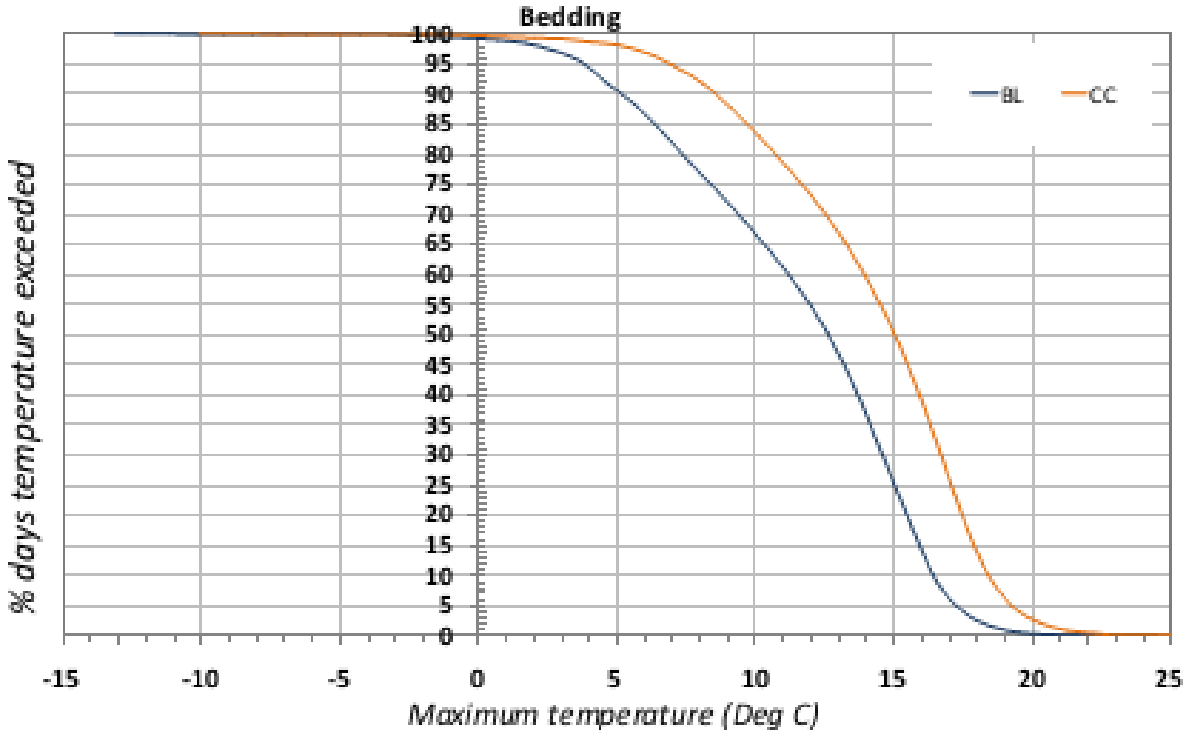


Figure 18 Projected increase in wet season mean monthly precipitation in Dolakha District between 2000 to 2050