Climate change impacts on glacial lakes and glacierized basins in Nepal and implications for water resources

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Abstract An increasing number of glacial lakes have been observed in recent years in Nepal and other Himalayan countries. Glacial lake outburst floods (GLOFs) causing destruction of life, agricultural land, hydropower installations, and other costly infrastructure have also occurred more frequently in recent years in Nepal, Tibet (China) and elsewhere in the Himalayas. Recent temperature and discharge data from the Tsho Rolpa glacial lake (4580 m a.s.l.) and two rivers from glacierized basins, Langtang (3900 m a.s.l) and Imja (4200 m a.s.l), were analysed. An increasing trend of warming and discharge were observed at high elevation. The potential impacts of climate change in Nepal Himalaya are likely to be seen in terms of increasing numbers of disastrous flood events, including GLOFs, and in the long-term reduced low flows. These will have implications for water resources development in Nepal and its neighbour, India.

Key words climate change; glaciers; glacial lake; glacial lake outburst flood (GLOF); low flow; water resources; Himalayas; India; Nepal; Tibet (China)

INTRODUCTION

Studies and observations made on a global scale have shown that although mountain glaciers have been retreating generally since the beginning of the last century, their retreat has accelerated since the 1980s (Dyurgerov & Meier, 1997; Haeberli & Hoelzle, 2001). The Himalayas, being the highest mountains of the world, have been profoundly impacted by climate warming, as shown by the rapid retreat of the Himalayan glaciers and appearance of glacial lakes in recent years (Hasnain, 1999; Fujita *et al.*, 2001a,b; ICIMOD/UNEP, 2001a,b; Chalise *et al.*, 2003, 2005; Rees & Collins, 2004; WWF, 2005).

The impact of climate warming on the glaciers and ice reserves of Nepal, China (Tibet) and other Himalayan countries will have serious implications for the freshwater reserve and consequently for low flows for Nepal and all other Himalayan countries. The total ice reserve of the Himalayas is approximately 3734.5 km^3 with 18 115 glaciers (Qin, 1999). According to Haeberli (1998), the wastage of the total Himalayan glacier ice reserve could contribute 16% of the total meltwater volume released from all the other glaciers and ice caps of the world excluding those of Antarctica and Greenland. Climate warming impacts in the Himalayas, therefore, have global implications .

CLIMATE WARMING IMPACTS ON GLACIAL LAKES OF NEPAL

Glacial lakes are found all over the Himalayas and the Tibetan Plateau. In general, comprehensive scientific data and information on the Himalayan glaciers and glacial lakes are not available. However, recent publications on glaciers and glacial lakes of Bhutan (ICIMOD/UNEP, 2001a), China/Tibet (LIGG/WECS/NEA, 1988; Qin, 1999) and Nepal (ICIMOD/UNEP, 2001b) indicate that glacial lakes are present in large numbers in these countries and some of them are growing dangerously.

The bursting of the Dig Tsho glacial lake in the Khumbu region of eastern Nepal on 4 August 1985 can be considered as the eye-opener and starting point for scientific investigation of glacial lake outburst floods (GLOF) and glacial lakes in Nepal and other countries of the Himalayas. The Dig Tsho GLOF lasted for only five hours but caused extensive damage for up to 40 km downstream, destroying human life, settlement, bridges and the near-complete Namche hydropower plant 12 km downstream (Ives, 1986; Vuichard & Zimmerman, 1986, 1987; Yamada, 1998). As this disaster occurred in the Everest region, it drew wide national and international scientific and public interest (Galay, 1985; Ives, 1986; Vuichard & Zimmerman, 1986, 1987). Prior to this other

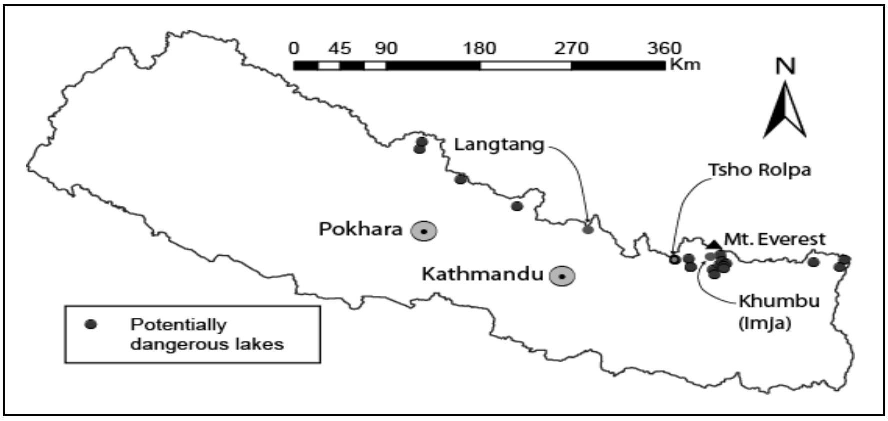

Fig. 1 Location map of high altitude stations (Langtang, Tsho Rolpa and Khumbu) and potentially dangerous glacial lakes in Nepal. Data source: ICIMOD/UNEP (2001b) and DHM.

GLOF events, including that in July 1981 in central Nepal on the Bhote Kosi and Sun Kosi rivers close to the China (Tibet) border were considered as catastrophic flash floods associated with extreme rainfall events during the monsoon. It was also apparent that GLOFs originating in Tibet (China) could cause damage across the border in neighbouring countries.

Almost all the glacier lakes in Nepal Himalaya are moraine-dammed (Yamada, 1998) and essentially unstable. According to a recent study there are 2323 glacial lakes in Nepal located at elevations of 3500 m a.s.l. and above, of which 20 are considered to be potentially dangerous (Fig. 1; ICIMOD/UNEP *et al.*, 2001b). Three of these potentially dangerous glacial lakes have past outburst history. Almost all of the potentially dangerous lakes are located east of Pokhara, in the central and eastern part of Nepal (Fig. 1). Similarly, of the 21 GLOF events reported so far all occurred east of Pokhara except one of unknown date which occurred in northwest Nepal (Mugu Karnali).

One of the reasons for this could be the higher monsoon precipitation in central and eastern Nepal compared to its western part. The other could be the impact of warming.

Most of the GLOF events occurred after the 1960s (ICIMOD/UNEP, 2001b). Shrestha *et al.*, (1999) analysed maximum temperature data for the period 1971–1994 and reported a warming trend in annual maximum temperatures from 0.06 to 0.12°C year^{-1} after 1977 for the middle mountains and Himalayan regions of Nepal. Another study of average annual temperature for 15 stations above 1800 m in Nepal has reported an annual increase of over 0.1°C year^{-1} for the period 1976–1996. (Rees & Collins, 2004) These values are more than double the +0.03°C year^{-1} average global warming predicted by IPCC (IPCC, 2001a,b). Investigation of climate change scenarios carried out by Shrestha (1997) also indicates that the warming trend at higher elevations will be more than at lower elevations. Furthermore, the large glacial lakes in Nepal (e.g. Tsho Rolpa and Imja) did not exist prior to the late 1950s when they started forming and grew rapidly to their present size. The growth rate of Imja Lake is 0.016 km^2 year^{-1}and Tsho Rolpa grew from 0.23 km^2 in 1959 to 1.76 km^2 in 2002. All these indicate a higher rate of warming at higher elevations in eastern Nepal Himalaya since the 1960s.

The first ever attempt to mitigate GLOF from a potentially dangerous glacial lake in the Himalayas was made in Nepal in 1999 for the Tsho Rolpa glacial lake (4580 m a.s.l.), i.e. lowering the lake height by 3 m by constructing a gated canal. The project was completed in 2003 and installed an Early Warning System (EWS) and a 15 kW micro-hydro power plant at the project site (DHM, 1998; Shrestha *et al.*, 2001, 2004; Chalise *et al.*, 2005).

In order to assess the impact of climate warming at higher elevations in the eastern part of Nepal, discharge data for Tsho Rolpa glacial lake for the periods 1993–1996 and 2000–2004 were analysed. The discharge from the natural outlet of Tsho Rolpa glacial lake was measured from June 1993 to May 1996 by the Glaciological Expedition in Nepal (GEN; Yamada, 1998). Since the completion of the construction of the open channel in June 2000 (Shrestha *et al.*, 2001), DHM has been monitoring the lake discharge through the open channel (Fig. 2). There is no visible difference between the two data sets for the periods 1993–1996 data and 2000–2004. Monthly

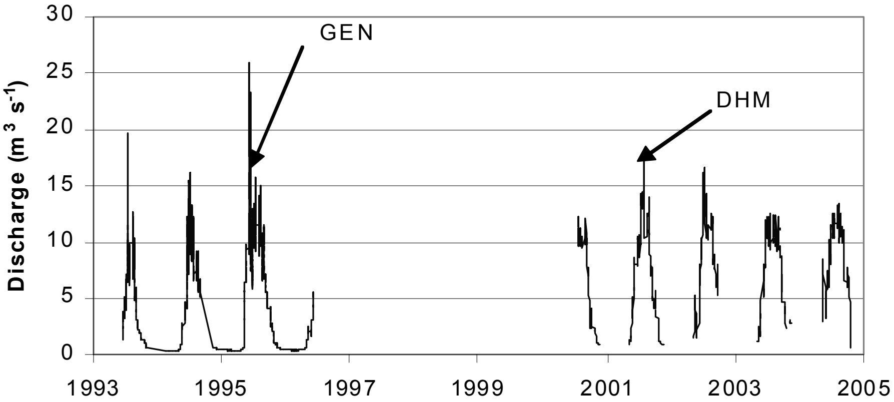

Fig. 2 Discharge from Tsho Rolpa Glacial Lake.

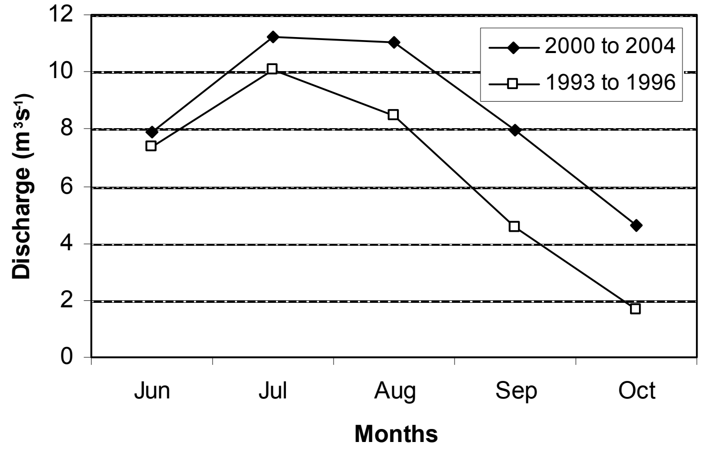

Fig. 3 Average monthly mean discharge at Tsho Rolpa.

mean discharges were computed for these two data sets covering the high flow period (June to October). It can be seen that the mean discharges of the latter period (2000–2004) is higher than that of the earlier period (1993–1996) for all months (Fig. 3). The difference in monthly mean discharge between these two periods is significant at $p > 95\%$. If this result is due to the intensification of melting in Trakarding and Trolambau glaciers (the parent glaciers of Tsho Rolpa) it can be anticipated that the lake level might start rising again and the risk of another GLOF will increase.

HYDROLOGICAL IMPACTS OF CLIMATE WARMING

In addition to the increased risk of the outburst of glacial lakes, climate change can have serious implications for the hydrological regime of the region as it is heavily dependent on the supply of water due to melting of snow and glaciers during the dry season (March–June). In order to assess the impact of atmospheric warming on dry season flows at higher elevations, temperature and discharge data from two high altitude hydrological and meteorological stations in Nepal, namely: Langtang (3900 m a.s.l.) and Khumbu (4200 m a.s.l.) were analysed. These stations were established in the late 1980s and have the longest climatological and hydrological records of the glacierized basins of Nepal. The Langtang station shows a distinct warming trend and the discharge from Langtang Khola shows a small but distinct increasing trend (Fig. 4). In contrast, neither temperature nor the discharge from Imja khola at Khumbu station show any trend.

The trends for Langtang might be an indication that climate warming has already started and is showing its impact on the river flows, although due to the short data period a definite conclusion cannot be made at this stage. A strong relationship exists between temperature and river discharge at both basins during the dry season, March–June (Fig. 5). This result supports the postulation that the hydrological regime of the Himalayan rivers will be affected by climate warming.

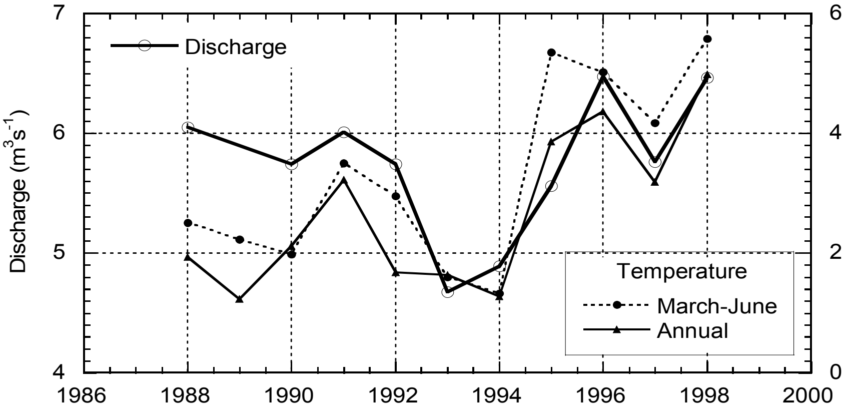

Fig. 4 Temperature and discharge at Langtang station.

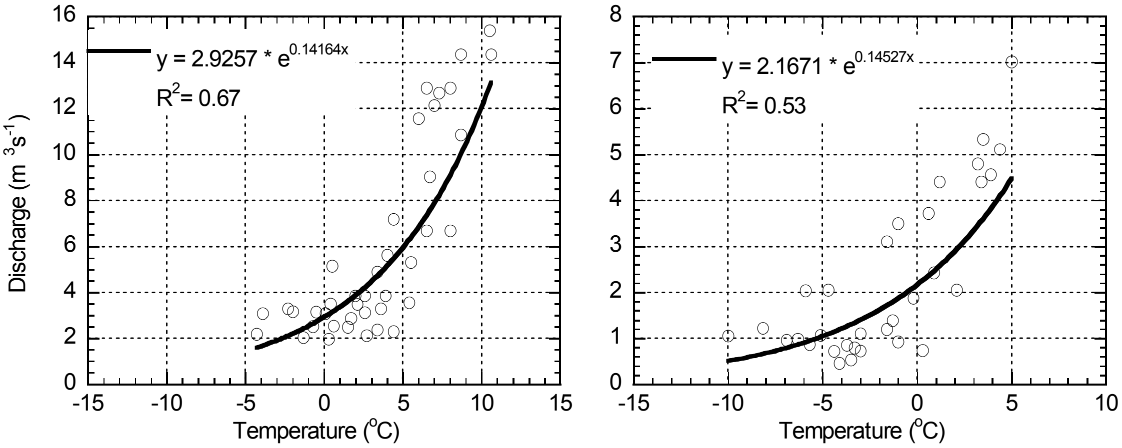

Fig. 5 Relationship between temperature and dry season discharge at Langtang (left) and Khumbu (Imja Khola, right)

IMPLICATIONS FOR WATER RESOURCES

Climate warming has two major implications for the water resources of Nepal, which show an increasing trend and impact at higher elevations. Firstly, the flash flood events, including GLOFs would increase due to increased melting of glacierized basins and glacial lakes. This will be further aggravated by the increase in summer precipitation including extreme precipitation events, due to global warming (Chalise, 1994; Shrestha, 1997; IPCC, 2001a,b). An increase in disastrous flash floods and GLOFs in the headwater regions would adversely affect the development of hydropower in Nepal. As a poor country with no other resources, Nepal hopes to develop its economy by exporting hydropower to its neighbours, particularly to India. With nearly 15% of its area (147 181 km^2) above 4500 m a.s.l. and under snow cover, Nepal is rich in water resources with a theoretical potential of 83 000 MW of which 42 000 MW is considered feasible and 22 000 MW exportable (NPC, 2003). The risk of major hydropower development in vulnerable, hazard prone areas could discourage large investments.

Secondly, the resource base, i.e. the ice reserve, is likely to shrink. This will seriously affect the dry season discharge in future. In general, the low flows in the Nepalese and other Himalayan rivers are at least 10–20 times smaller than the high flows. With a shrinking resource base the dry season flows are likely to decrease too. This will seriously affect not only the development of hydropower but also agricultural and industrial development, apart from causing acute shortage for human consumption.

The decrease in dry season flow in the Nepalese rivers is also going to affect the flow in the Ganga (Ganges) in India as all the Nepalese rivers drain into the Ganga. Although Nepal constitutes only 13% of Ganga basin by area, Nepalese rivers contribute 47% of the annual discharge of 382 000 million m^3 of the Ganga at Farakka and their contribution is 75% for the three dry season months from March–May (Pun, 2004). A decrease in low flow in Nepalese rivers would also adversely affect the Ganga dependent areas in Bangladesh. The river linking project of India, which intends to link the Ganga and Brahmaputra rivers with the rivers in peninsular India (Prabhu, 2004) could also be affected.

CONCLUSION

Increasing deglaciation in Nepal and other Himalayan countries due to a warming climate will further intensify the "too much" (during the short wet period) and "too little" (during the long dry periods) situation in these countries. Identification of rapidly growing glacial lakes and increased understanding of their growth mechanism are important to develop strategies to cope with and mitigate the future disastrous GLOF events. It is urgent for these countries start sharing available relevant information and data, and work together to develop a comprehensive scientific database to develop national and regional strategies to cope with the potential impacts of climate warming on their snow and ice reserves. International scientific networks such as ICSIH/IAHS and the regional network of UNESCO's FRIEND project, viz. the Hindu Kush-Himalayan FRIEND, which are already contributing to improve scientific understanding of climate change impacts on the Himalayan cryosphere, should be encouraged to contribute to the national and regional research programmes.

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