

On the formation of supraglacial lakes on debris-covered glaciers

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Abstract Analyses of satellite imagery obtained in 1989–1990 and topographic maps from 1966 have been undertaken for the glacierized areas of Bhutan. It has been found that where supraglacial lakes have formed since 1966, surface gradients of the glaciers concerned were in all cases less than 2°. At gradients of 2–10° supraglacial ponds can form but tend to be transient due to the opening and closing of crevasses. By identifying the conditions under which large supraglacial lakes form it is possible to use these criteria to predict where such lakes may develop in the future. This will allow suitable monitoring programmes to be introduced and, where necessary, suitable engineering remediation works to be undertaken in order to prevent the collection of large volumes of water that may be liable to form glacier lake outburst floods in the future.

INTRODUCTION

In October and November 1998 the author was commissioned by Norconsult A.S./NORPLAN Joint Venture to participate in a pre-feasibility study for a major hydropower project in Bhutan (Fig. 1). The project was undertaken in collaboration with the Division of Power, Royal Government of Bhutan. The author's task was to compile the first detailed inventory of glaciers and glacial lakes and to undertake the first assessment of glacial hazards in the Mangde Chhu River basin and to review the glaciers of Bhutan with respect to the formation of glacial lakes and their prospective rupture to form what are known in the Himalayas as Glacier Lake Outburst Floods (GLOFs). Images of over 300 glaciers were examined with 154 being studied in detail.

As part of the project access was provided to 1:50 000 scale prints of sub-scenes of panchromatic SPOT imagery of the whole of Bhutan. The imagery was obtained in December 1989 and in December 1990. Access was also provided to colour SPOT imagery at a scale of 1:125 000 obtained in December 1993 of the Lunana area in northern Bhutan. In addition, a set of topographic maps at the same scale and produced by the Survey of India was also made available. These maps dated from 1966 and were based on aerial photography acquired in 1956 and 1958 at an approximate scale of 1:32 000 with further ground truth provided in 1960–1962. It was clear from comparing the satellite images with the topographic maps that many of the glaciers present in 1958 had developed lakes over significant areas. While many glaciers exhibit supraglacial ponds that appear to be transient, some supraglacial ponds develop to form a single large supraglacial lake. This may develop further to lead to the separation of a significant stagnant or very slow moving ice mass from the upper reaches of the glacier. The formation of such lakes poses a potential threat should the

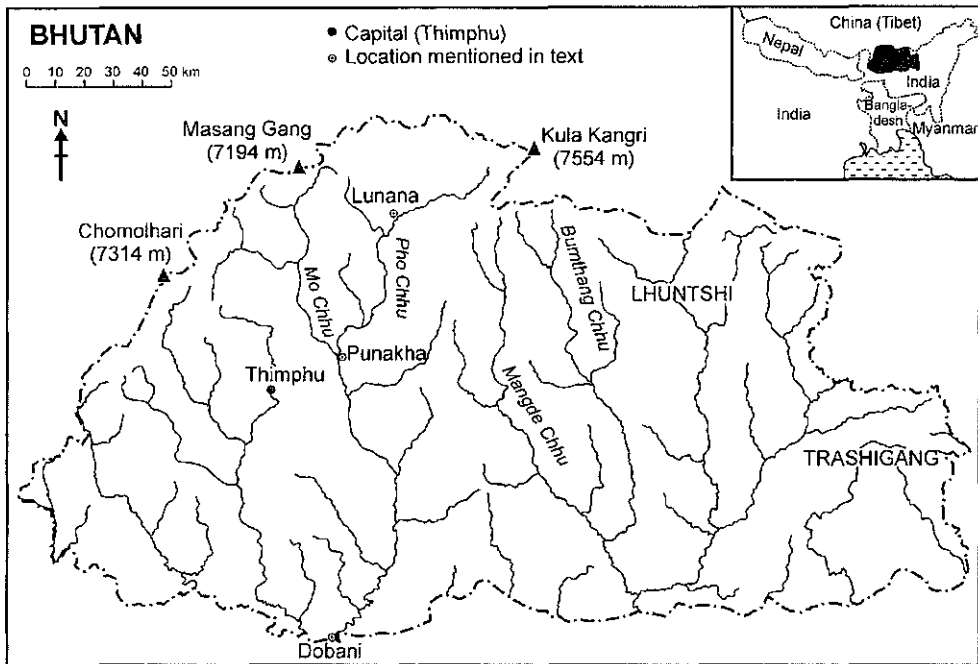


Fig. 1 Map of Bhutan indicating principal rivers and locations named in the text.

lakes burst through whatever is damming them. In the Himalayas there are many records of such catastrophic outbursts from moraine-dammed supraglacial lakes (Galay, 1987; Ives, 1986; Reynolds, 1998a; Yamada, 1993) resulting in loss of life and significant amounts of damage to property and strategic infrastructure. In Bhutan, 27 people were killed at Punakha following the outburst from Luggye Tsho (Fig. 2), Lunana region, in the eastern branch of the Pho Chhu on 7 October 1994.

Analysis undertaken by the present author of the SPOT imagery for Bhutan has indicated a large number of potentially dangerous glacial lakes in Bhutan and no river system that drains from the high Himal is immune. Consequently, it is of considerable importance to Bhutan for strategic reasons that such glacial lakes are identified and areas where other lakes may form are identified for planning purposes, and especially in relation to the development of hydropower (Reynolds, 1998b).

As glaciers continue to recede in response to climate change, the number and volume of potentially dangerous glacial lakes in the Himalayas are increasing (Richardson & Reynolds, 2000a). Consequently it is important to be able to recognize how such lakes have formed in the past and thus where they may form in the future.

PHYSICAL SETTING IN BHUTAN

Bhutan comprises an area of 47 182 km² on the southern boundary of the Tibetan Plateau. Ground elevations range from less than 300 m on the southern border with northern India to over 7000 m in the northern high Himal. Bhutan is dissected approximately north-south by major river systems that drain the high mountains

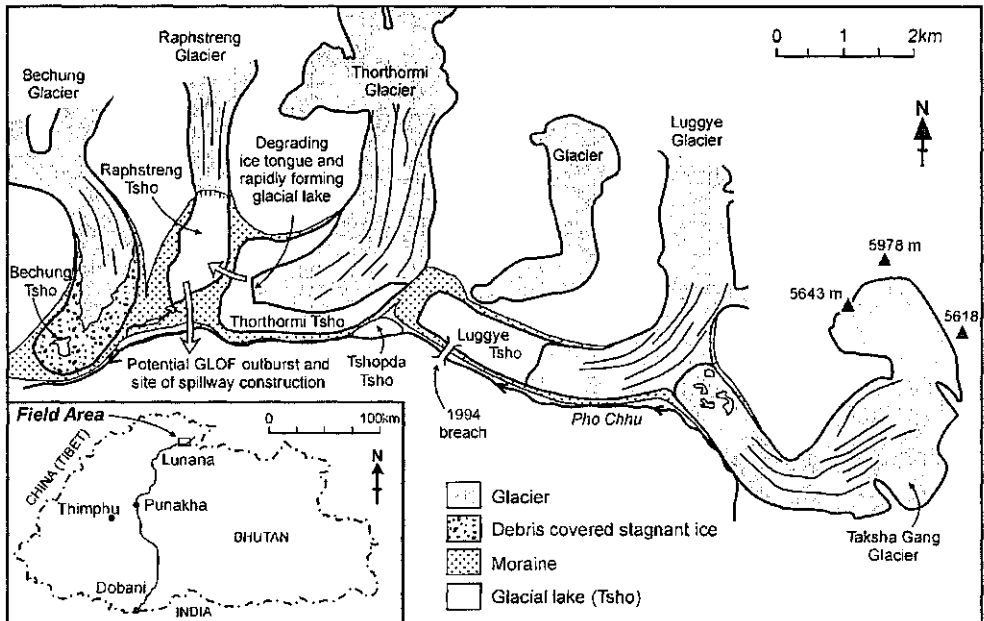


Fig. 2 Relationship between the key glaciers in the Lunana area (shown at their 1962 extent). Tshoju Glacier is located about 5 km west of Bechung Glacier.

towards the south and into northern India as tributaries of the Brahmaputra River which then flows through Bangladesh.

The main areas covered by glaciers are the high Himal in the northern part of the country and especially in the west (east of Chomolhari, 7314 m) and central regions (south of Masang Gang, 7194 m, and Kula Kangri, 7554 m) and to a lesser extent in the regions of Lhuntshi and Trashigang in the east. The glaciers range from small remnant cirque and niche glaciers through to major icefields and outlet and valley glaciers in the north. The highest glaciers appear to be dominated by radiation and may be cold-based as many of them produce little meltwater. In common with other similar regions of the Himalayas, the glaciers in Bhutan are generally in recession although there appear to be some exceptions that are at least maintaining their spatial extent in the short term (decadal scale).

PREVIOUS GLACIOLOGICAL STUDIES IN BHUTAN

There have been no previous specific glaciological investigations in Bhutan that have been published other than as part of other broad geological studies (Gansser, 1983). However, a desk study on glacier lakes was undertaken by Norconsult and Norpower as part of the "Bhutan Power System Master Plan Project" in 1992–1993. A review of available satellite imagery was carried out by the Division of Geology and Mines (DGM), Ministry of Trade and Industry (Norbu, 1996). Both desk studies were reviewed and the primary data re-analysed by the present author as part of the commission with Norconsult/NORPLAN and the Division of Power in October/November 1998. The results of this work have been described within the

official project report submitted to the Royal Bhutanese Government in 1999. The only other previous literature relating to glaciers and glacial lakes in Bhutan are unpublished reports relating to investigations into potentially problematic glacial lakes near Lunana (Sharma *et al.*, 1984, 1987) and into the GLOF from Luggye Tsho in the Lunana area in October 1994 (Tashi, 1994; Bhargava, 1995; Leber *et al.*, 1999).

Following the review and analysis undertaken by the author, and building upon the extensive previous experience in the Nepalese Himalayas (Reynolds, 1998a, 1999), in the Andes (Reynolds, 1990, 1992, 1998b; Reynolds *et al.*, 1998), as well as in the Antarctic (Reynolds, 1981) it has been possible to consider the formation of supraglacial ponds and lakes.

SURFACE TOPOGRAPHY AND PRESENCE OF SUPRAGLACIAL LAKES

By comparing the 1966 topographic maps at a scale of 1:50 000 for Bhutan with the 1989–1990 SPOT imagery, it has been possible to consider the changes in the glaciers over the intervening 23–24 years and to identify why lakes form on some glaciers but not others.

Two areas in Bhutan (Fig. 1) were considered in detail: the Lunana region, due to the GLOF of 1994 and to its significance with respect to ongoing glacial lake remediation and hazard minimization (Leber *et al.*, 1999), and the Chomolhari area. In both areas, longitudinal profiles were taken from the 1966 topographic maps through glaciers that had subsequently developed large supraglacial lakes as well as neighbouring glaciers that had not. The longitudinal profiles from both sets of glaciers (with and without lakes) were compared and the longitudinal gradients examined.

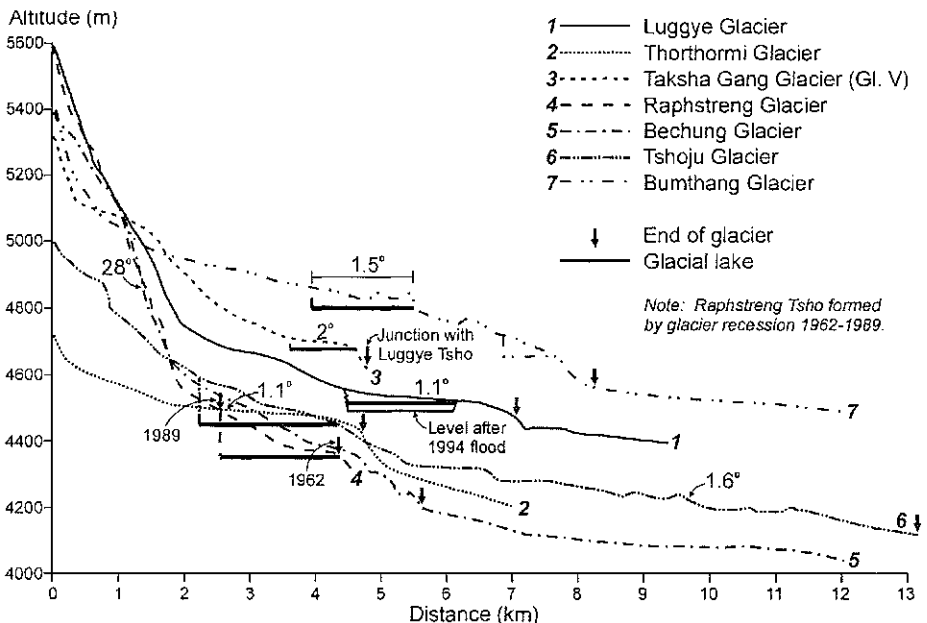


Fig. 3 Elevation profiles of six glaciers in the Lunana area of Bhutan with one from the Bumthang Chhu. The locations of large supraglacial lakes are indicated.

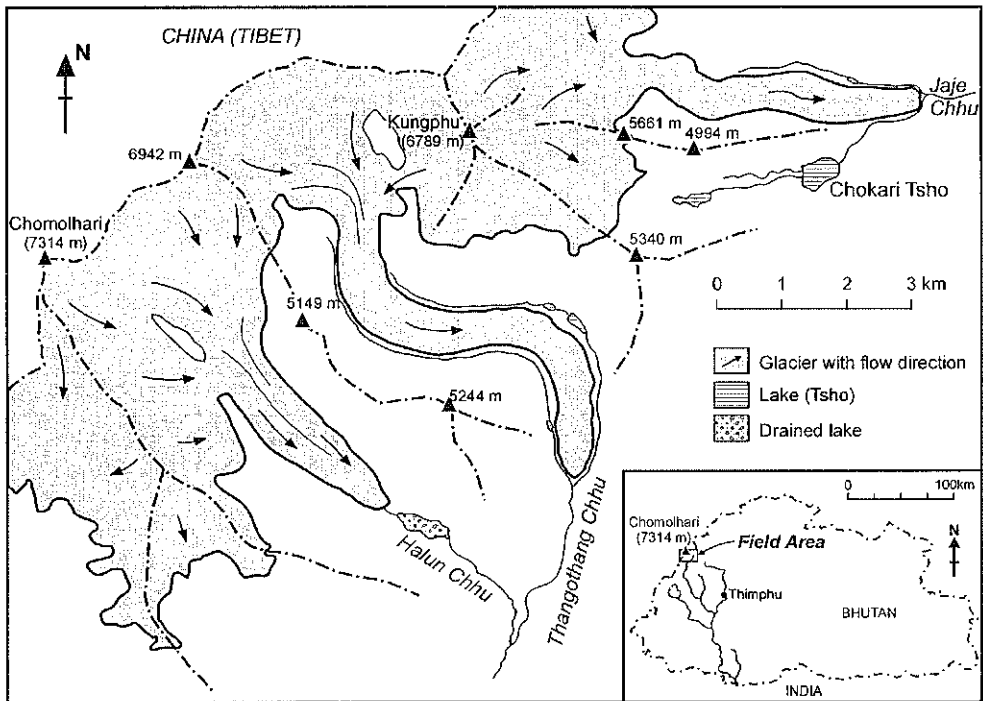


Fig. 4 Relationship between the named glaciers in the Chomolhari area in west Bhutan (shown at their 1962 extent).

The location of and relationships between selected glaciers in the Lunana area are shown in Fig. 2. The corresponding longitudinal elevation profiles are shown in Fig. 3 with the positions of the supraglacial lakes that had formed between 1966 and 1989 indicated. A longitudinal profile from the Bumthang Glacier, from the upper headwaters of the Bumthang Chhu (Fig. 1), is also shown.

The glaciers all have extremely steep headwalls, with elevations from 5600 m down to 4600 m, from which the glacier surfaces level out. In each case where a large supraglacial lake has developed, the glacier surface prior to 1966 had a slope of less than 2° . Where slopes were between 2° and 6° , discrete supraglacial ponds were evident. For slopes greater than 6° but less than 10° , small isolated ponds could be found. For slopes greater than 10° there was no evidence for supraglacial ponds.

Similarly a set of glaciers east of Chomolhari has been examined whose locations are shown in Fig. 4 with their corresponding longitudinal elevation profiles in Fig. 5. It is again evident that supraglacial lakes form at the shallowest surface gradients.

DISCUSSION

It appears that for supraglacial ponds to develop into larger supraglacial lakes the surface slope should be $<2^\circ$. However, shallow slope angles in themselves are not sufficient for the formation of supraglacial ponds. There must be appropriate mass balance conditions to permit the formation of sufficient meltwater. It has been found in

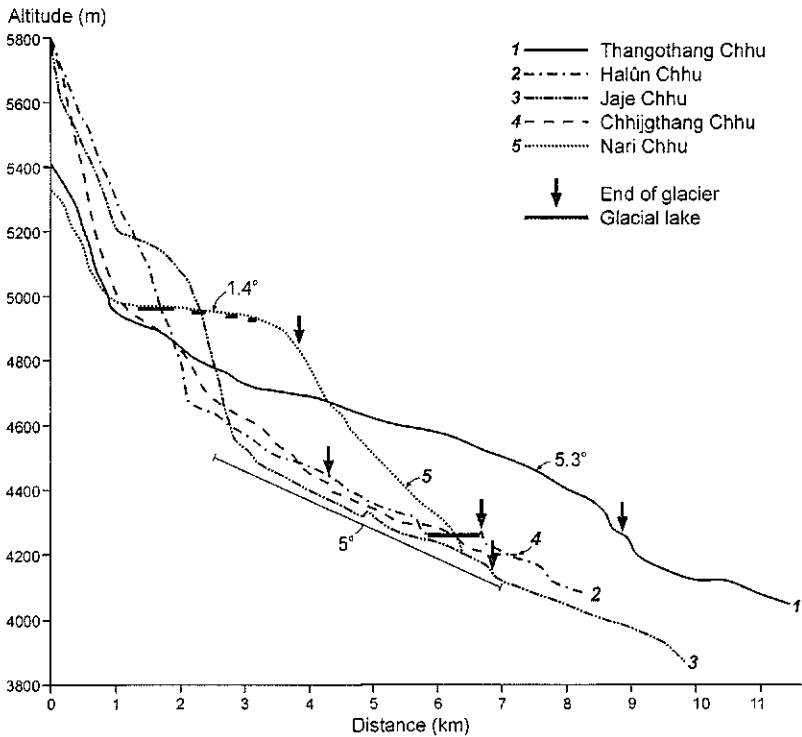


Fig. 5 Elevation profiles of five glaciers in the Chomolhari area in west Bhutan. The locations of large supraglacial lakes are indicated.

the Antarctic, for example, that large supraglacial ponds and lakes form when the surface slope is virtually flat, the local mass balance is in effect negative, the surface has low surface permeability and the drainage off the ice is limited (Reynolds, 1981). This restriction is usually due to the surface being flat.

Once a pond has formed it has a lower albedo than that of the surrounding snow and ice. Consequently, absorbed radiation into the water helps to develop further melting. Debris on adjacent ice may help to insulate it from radiation melting. As a pond develops its margins tend to steepen. Debris on the pond margins sloughs into the pond exposing adjacent glacier ice that then melts faster. Sub-aerial ice melts by backwasting and, given steep or near vertical ice cliffs, the local ice may respond rheologically and fail mechanically. These processes only serve to exacerbate the rate of pond development (Richardson & Reynolds, 2000b). Where algae begin to colonize the edges and floors of ponds, they can provide biological heating to the local water and increase the rate of melting of local ice substantially. For example, at Thulagi glacier lake in Nepal, measurements of temperature were made using a thermistor within a number of ponds on debris-covered ice. The lake water was generally found to be $1.4 \pm 0.3^\circ\text{C}$. When the thermistor was placed just inside a mat of green algae the temperature was found to be 6.3°C . Elsewhere, temperatures within algae mats were found to be between 5 and 8.5°C warmer than those of the surface water. Where temperature profiles with depth were completed, temperature gradients of around 5°C m^{-1} were found over shallow depths of 1–2 m. The measured temperatures were

highest in the most dense concentrations of green algae. Biogenic heating of ponds over ice would appear to be significant where algae have become established. Once formed, lakes tend to be self-perpetuating through a combination of the above processes as long as the water remains in the pond.

It is also evident that once ponds have formed and the glacier surface lowers through ablation, they coalesce to form larger lakes. Eventually all the lakes will merge to form one large supraglacial lake. It is known from repeat observations that this process can take up to several decades to complete (Mool, 1995; Watanabe *et al.*, 1994). However, there are also examples in South America where this process can occur in less than 10 years (e.g. Hualcán, Cordillera Blanca, Peru; Reynolds, 1989).

The flow activity of a glacier is inherently related to surface slope (due to its relation to basal shear stress and to the general rheological flow of ice that is also dependent upon basal shear stress (Paterson, 1994)). Consequently, the steeper the surface slope the more active the flow is likely to be. Given the complex structures found in Himalayan glaciers, both within individual flow units and as composite glaciers, the surface structures (e.g. crevasses) are likely to open and close intermittently and thus allow drainage of surface water into and within the glacier. Transient supraglacial ponds are common on Himalayan glaciers. The relationship between glacial structures and supraglacial drainage is well known (e.g. Benn & Evans, 1998, p. 106; Reynolds, 1981). Further evidence for the control of glacial structures and flow dynamics on the shape of supraglacial lakes is also demonstrated by reference to Fig. 6. This shows a glacier in Bhutan (near Kajila, on the Nari Chhu, an upper tributary of the Mho Chhu) where there is a clear sequence with position downstream of the orientation of pear-shaped supraglacial lakes. With increasing distance downstream, the long axis of each pond rotates from being oblique to become transverse (Fig. 6). Furthermore, the ponds have formed in a depression caused by the junction between two convergent flow units. This example serves to reinforce the relationship between glacier structure and supraglacial drainage.

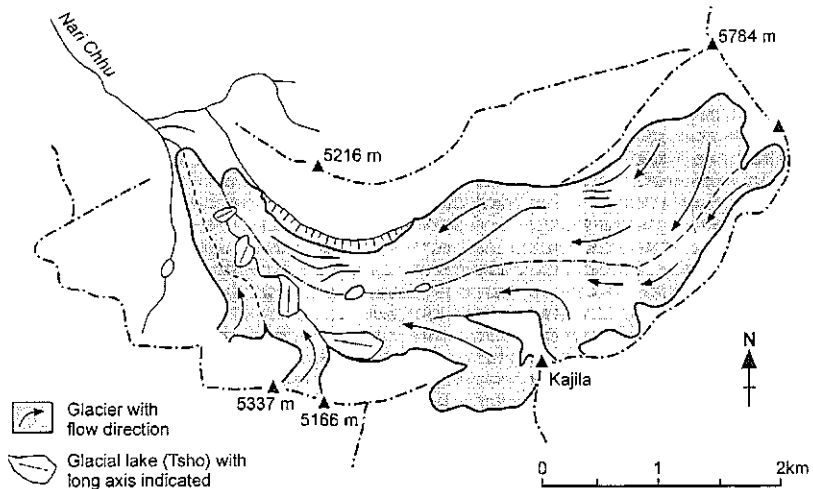


Fig. 6 Map of Kajila Glacier indicating the form of four supraglacial ponds that appear to have rotated from parallel to transverse to glacier flow with distance downstream.

Assuming that supraglacial lakes form where the surface gradient is $<2^\circ$, given a negative mass balance, it should be possible to identify locations where such lakes may form in the future. If the proto-lake formation takes a decade or more, this may yield an early warning lead-in time of a similar time period sufficient to establish appropriate monitoring and maybe even early engineering remediation works to stop significant volumes of water forming. This may be prudent as part of a risk management strategy in locations where key infrastructure lies downstream. This is especially valid given the precarious nature of many glacial lakes in most river systems in Bhutan. Such monitoring procedures should be established urgently.

CONCLUSIONS

Meltwater forms on the surface of glaciers where the appropriate mass balance conditions exist. Flow activity within the glacier may cause structures to open and close giving rise to intermittent drainage of meltwater. However, the controlling factor that appears to influence the formation of supraglacial ponds is the glacier's surface gradient:

- *Surface gradient $>10^\circ$* = all meltwater is able to drain away, no evidence of ponding;
- *Surface gradient in the range $6-10^\circ$* = isolated small ponds may form, transient due to local drainage conduits opening and closing due to ice flow;
- *Surface gradient in the range $2-6^\circ$* = supraglacial ponds form, may also be transient locally, but sufficiently large areas affected by presence of ponds;
- *Surface gradient in the range $0-2^\circ$* = formation of large supraglacial lake over stagnant or very slow moving ice body forms from the merging of many smaller discrete ponds.

By identifying areas with a surface gradient of less than 2° on glaciers with a negative mass balance, it should be possible to establish appropriate monitoring or even early engineering remediation works to stop the formation of large volumes of water that may later prove to be potentially dangerous. Given the precarious nature of many glacial lakes in most river systems in Bhutan, such monitoring procedures should be established urgently.

Acknowledgements I am very grateful to Dr Shaun D. Richardson, Reynolds Geo-Sciences Ltd, for fruitful technical discussions and for producing the figures. I am also very grateful to Mr Dorgi Namgay, Division of Power, Ministry of Trade and Industry, Royal Government of Bhutan, and Mr L.-E. Lørum and colleagues, Norconsult/NORPLAN Joint Venture, for inviting me to become involved with this work in Bhutan and for permission to publish the results.

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