Managing glacial hazards for hydropower development in the Himalayas, Hindu Kush and Karakoram

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1. Introduction

It has been widely reported in the media that the glaciers of the Himalayas are shrinking, which is manifest in prevalent glacier retreat, whilst many of those in the Karakoram are stable or flourishing. Changes in the glaciers across the region impact on water resources, hydropower development, tourism, and affect mountain hazards. Of growing interest in recent years has been the issue of glacial hazards, such as ice dam failures or more specifically, Glacial Lake Outburst Floods (GLOFs), which can cause widespread devastation downstream and may pose a significant threat to hydropower schemes. In 1985, the Dig Tsho HEP scheme in Nepal was destroyed two weeks prior to its inauguration by a GLOF from an upstream glacial lake. Given the demand for power generation in the region and the significant planned capacity for hydropower over the next decade this issue merits greater attention than it has received hitherto.

This article provides an introduction to glacial hazards across the Hindu Kush, Karakoram and Himalayas and how they can be monitored and managed with respect to hydropower development. A brief overview of glacial hazards assessment in relation to hydropower projects has been given in a companion paper by Reynolds (2014).

2. Climate change and glaciers

There are two main climatic systems that affect the glaciers across the Hindu Kush, Karakoram and Himalayan Region. The Hindu Kush and Karakorum mountains are dominated by mid-latitude westerly wind systems, which have strengthened in recent decades, resulting in more snowfall (Mölg *et al.*, 2014). Most of the glaciers in this area are stable if not flourishing (Bolch *et al*., 2012) and advancing and especially those in the Karakoram are showing surging behaviour (Rankl *et al*., 2013). Surging glaciers undergo periods of accelerated ice flow speeds that can lead to rapid advance of the glacier terminus, marked changes to the glacier's surface morphology and topography, and to the distribution of water within the glacier system. The complex processes relating to glaciers surges are as yet still not properly understood (Hewitt, 2007). A surging glacier may advance into and block a downstream valley, resulting in the rapid ponding of water and formation of large volume (multiple cubic kilometres) of water behind an ice dam. Historic failures of such ice dams in the Karakoram in the early 20th century have resulted in massive floods (2-3 km^3) with run-out distances in excess of 1,200 km.

In contrast, the Indian Summer Monsoon, which dominates the south side of the Himalayas, has weakened and lengthened, which has resulted in less snowfall to nourish the glaciers. Himalayan glaciers are undergoing significant shrinkage both by area and volume. This has serious consequences for glacial melt and river flow and on the use of this water by communities and hydropower schemes. There is also high confidence that permafrost temperatures have increased in most regions since the early 1980s (IPCC, 2013). Whilst this relates predominantly to the high latitudes, especially the Arctic, there is empirical evidence that permafrost at altitude in places like the Andes, European Alps and Himalayas is also being affected by rising temperatures. The consequences are being seen as increased high-altitude rock and ice avalanches. Furthermore, high-altitude glaciers appear to be *cold-based*, *i.e.* are well below their pressure melting point, are frozen to their base, and lose mass predominantly through sublimation. Those at lower altitude are either *temperate*, *i.e.* are at the pressure melting, are not frozen to their base, and lose mass predominantly through melting or *polythermal* (higher-altitude parts cold-based, lower-altitude parts temperate).

One of the manifestations of this increasing glacial recession across the Himalayas especially is the consequential growth in glacial lakes. As a glacier retreats from the terminal moraine formed at the time of its glacial maximum position, water collects behind the moraine and forms a lake. When the restraining dam fails, for reasons explained later, a Glacial Lake Outburst Food is initiated. One such outburst of ~18 million m³ from Luggye Tso in northern Bhutan in 1994 resulted in 21 deaths and widespread damage downstream; the flood wave still had an amplitude in excess of 2 m when it crossed the international border between Bhutan and India, a distance in excess of 200 km from the flood's source.

2. Hydropower development in Bhutan, India, Nepal and Pakistan

The high mountains that form the Pamir, Hindu Kush, Karakoram and Himalayas have enormous potential for hydropower development. There is currently in excess of 24 GW installed hydropower capacity across the region with projects in construction and planned within the next decade totalling a further 101.8 GW. In many areas, the impact of climate change on the glacier systems upstream of hydropower scheme must be taken into consideration if they are not to suffer the same fate as that of Dig Tsho in Nepal in 1985. It is important that glacial hazards are evaluated and managed at two stages in any hydropower scheme's life: during construction, when perhaps the scheme is most vulnerable due to engineering works in the process of being built and to larger numbers of workers present at the site; and post-construction. It is for these reasons that the issues of assessing and managing glacial hazards need to be addressed.

3. Glacial outburst floods and their impacts

From work undertaken in Bhutan (Reynolds, 2000) and detailed monitoring of glacier flow using remote sensing techniques (Quincey *et al*., 2007) how glacial lakes form is now well understood. For the lowermost parts of glaciers where the net mass balance is negative, the surface gradient is <2° and ice is stagnating with no or only minimal movement, large supra-glacial lakes can form. Coupled with this, the tell-tale signs of early pond formation and transition from transient to perennial status can be deduced by observation, including as a first pass, by inspection of suitable remote sensing imagery. An overview of glacial hazards in the Himalayas has been provided by Richardson and Reynolds (2000b).

In the case of surging glaciers, impounded reservoirs form when an advancing glacier tongue flows across and blocks a river valley. Given the flow rates of many rivers in the Karakoram, it takes a relatively short time to build up a significant volume of water, perhaps of the order of days to a few weeks. Once the dammed water level rises enough, the water pressure may become sufficient to jack up the ice dam hydraulically thereby releasing water sub-glacially, which may in turn lead to the disintegration of the dam and the further catastrophic release of the stored water downstream.

Moraines can fail from internal piping leading to mechanical failure; melting of buried ice within the moraine through thermokarst processes leading to subsidence and thence failure; overtopping by a single wave that causes regressive erosion and subsequent failure or by a sequence of overtopping waves until failure is achieved, or seismically-induced failure. Each will generate a different form of breach and a subsequent flood event with a different hydrograph shapes, complexity and duration. GLOF peak flow rates can reach 2,500 m³/s to over 10,000 m³/s. Assumptions about how a given moraine may fail and the form of the subsequent flood can make a huge difference when it comes to modelling flood behaviour.

4. Assessing glacial hazards

As most glacierised areas in high-mountain regions are remote and therefore difficult to visit without significant and expensive logistical effort, remote sensing techniques have come to the fore over the last two decades by which first-pass hazard assessments over large areas (100s of km²) can be undertaken (Quincey *et al*., 2005, 2007; RGSL, 2002a,b, 2007). Very-high-resolution imagery (<1 m ground resolution) and associated Digital Elevation Models can be used for more geographically-restricted areas (*e.g.* <10 km²) for more detailed assessments of specific glacial lake systems. The results from such analyses can be used to design field programmes that merit the investment. These may include, for example, detailed geomorphological, geophysical, topographical and engineering geological surveying and mapping, such as described by RGSL (2003) and Hambrey *et al.* (2008). Further details on assessing glacial hazards have been given by Reynolds (2014).

5. Glacial hazards across the region

5.1 Nepal

In Nepal two lakes are of particular significance by way of discussion: Tsho Rolpa, in Rolwaling, which is thought to be the most hazardous lake in Nepal, and Imja Tsho, in Solukhumbu, which some say is the most hazardous lake in Nepal but which the evidence suggests otherwise.

Tsho Rolpa has been the subject to significant research (Reynolds, 1998a) leading to its interim remediation by way of an open channel and sluice gates (Figure 1a,b) completed in July 2000 (Reynolds, 1999; Rana *et al*., 2000). Part of the justification for remediating this lake was the presence of the Khimti II hydropower scheme downstream. Subsequent to this has been the development of access infrastructure for the Upper Bhote Kosi HEP scheme at Lamabaga; the part below the confluence with the Rolwaling Kola is vulnerable to any GLOFs from Tsho Rolpa. Glacial lakes upstream of Lamabaga lie within Tibet (China). It was proposed in 1994 that the lake level should be lowered by 20 m to provide longer term remediation. Although the lake level was lowered by 3.5 m in 2000 as an interim remediation stage, no further mitigation work has been proposed. However, it is clear from extensive geophysical investigations undertaken across the terminal moraine prior to the remedial works and multiple field observations of debris-covered islands (Figure 2c) that they have been subsiding over time (Richardson and Reynolds, 2000b). This indicates that a significant mass of stagnant ice (of the order of 10 million m^3) remains grounded on the lake floor. Unless the current lake level is significantly lowered, there will come a time when the stagnant ice mass will become instantaneously buoyant, which could result in the collapse of much of the current 150-m high moraine dam. Under this scenario, the potential flood volume could be of the order of 80-125 million m^3, with potentially devastating consequences downstream. If the water level can be reduced by the remaining 16.5 m or so, the buried ice will remain grounded for much longer. If over time, and subsequent to this final lake level lowering, the ice were then to become buoyant, it would be anticipated that the 20-m+ freeboard of the terminal moraine and the wider dam resulting from the water level being lowered would provide sufficient resistance to any waves generated by the buoyancy process.

Figure 1: (*Top*) The open channel and outer sluice gate at the western end of Tsho Rolpa, Rolwaling, Nepal. (*Bottom, left*) the gabion wall and distal side of the sluice gate viewed from downstream of the channel; and (*bottom, right*) islands of debris covered-ice atop a large submerged stagnant ice body, the approximate extent of which is indicated.

In contrast, Imja Tsho (Figure 2) has achieved a degree of notoriety in the Solukhumbu with local residents angry at repeated claims in 2008 and 2011 as to the imminence of the failure of the lake's dam, resulting on one occasion in local residents evacuating their homes overnight in panic. Whilst Imja Glacier is retreating up-valley and the upstream side of the debris-covered stagnant ice mass within the terminal moraine complex is gradually migrating downstream as the ice melts, there are no changes evident in the parameters affecting its hazard rating

(Reynolds, 2014). Extensive geophysical investigations and detailed geomorphological investigations (Hambrey *et al*., 2008) indicate that the lake poses minimal hazard. The Imja glacial lake system comprises: a broad area of stagnant debris-covered ice (indicated by the dashed blue line in Figure 2) and residual ice-free debris area behind the moraine; low-gradient distal slopes of the terminal moraine; and intact lateral moraine ridges (yellow arrows in Figure 2) indicating no previous avalanche activity directly into the lake. These demonstrate the lack of trigger processes that could generate a GLOF from this lake and hence why the lake should be designated as posing only a minimal hazard.

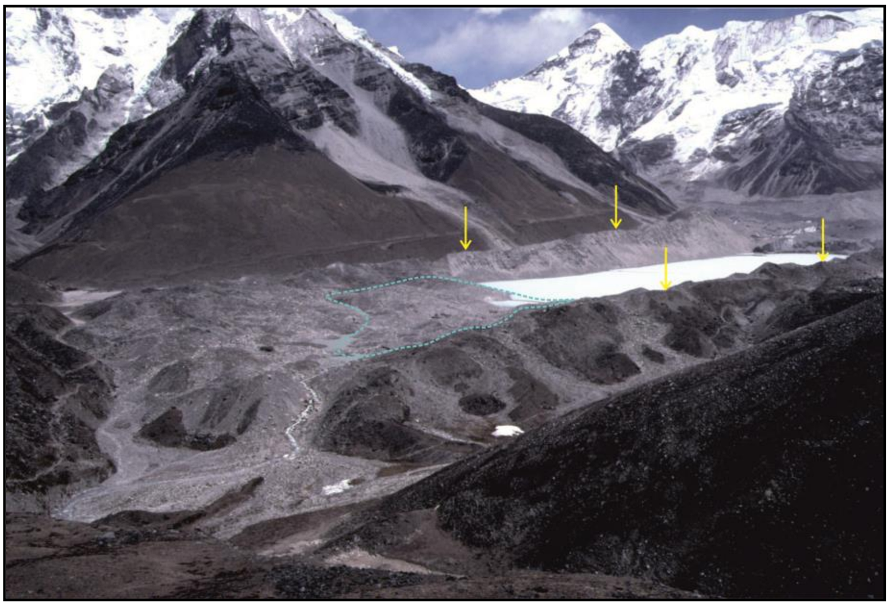

Figure 2: Imja Tsho as seen in 2003. The intact lateral moraine is indicated by yellow arrows. The area of debris-covered stagnant ice is shown by the dashed blue line.

As it is known that supra-glacial lakes develop where a glacier's surface gradient is <2°, it is possible to map prospective lake growth (Quincey *et al*., 2007). For example, Imja Glacier could double its current length to 4.4 km length whereas Lhotse Glacier, also in the Solukhumbu, Nepal, has and will have supra-glacial ponds on its debris-covered surface but the surface gradient is too steep for any large supra-glacial lake to form. Significantly, the nearby Ngozumpa Glacier is forming supra-glacial ponds in the snout area immediately behind its terminal moraine (Benn *et al*., 2012) and, with the known extent of the flat-lying part at <2°, could form a lake of the order of 9 km long (area ~6.5 km^2; volume ~330 million m^3 depending on the lake depth).

4.2 Bhutan

An initial glacial inventory was undertaken by the Division of Geology and Mines and published in 1999 (Norbu, 1999). The first comprehensive glacial hazard assessment of the whole country was undertaken by the present author in 1998 as part of a re-evaluation of the Bhutan Power System Master Plan Project (Reynolds, 2000) that was extended in 2002 (RGSL, 2002a). Of the many glacial lakes in Bhutan, especially in the Lunana area of northern Bhutan (Figure 3), the one causing greatest concern by far has been the supra-glacial lake that has developed on Thorthormi Glacier, as shown in Figure 4 (Norbu, 1999; Richardson and Reynolds, 2000a; Reynolds, 2000). In 2000, the lake was considered to have a volume of the order of 83.5 million m^3; a more recent estimate gives the enlarged lake a volume of 153 million m^3, although both of these are probably significant underestimates as the lake hypsometry has not been measured. However, should the right lateral moraine of Thorthormi Tsho fail and also take out the terminal moraine at Raphstreng Tsho, the combined GLOF volume could be of the order of 110-155 million m^3; this compares with 18 million m^3 estimated for the GLOF from Luggye Tso in 1994. Recognising the seriousness of the situation at Thorthormi Glacier, the Royal Bhutanese Government with the aid of the UNDP, has established a programme for an Early Warning System along the Pho Chhu valley coupled with a programme to reduce the water level of Thorthormi Tsho by 4 m. Whilst this, if completed successfully, will provide some short term relief, it is unlikely to reduce the overall hazard relating to the potential failure of the right lateral moraine at Thorthormi, which could result in a breach size 30-50 m deep, if not more. Given the existing hydropower schemes at Basochhu south of Wangdue Phograng and the intent to construct two large projects (Punatsangchhu I and II) along the same river, the implications of such a major potential GLOF from the Lunana area at the headwaters of the Phu Chhu should be fully considered.

Glacial lakes currently exist in the upper catchments of all the major rivers in Bhutan, except for Amo Chhu and Ha Chhu in the far south west. Kuri Chhu, in the east of Bhutan, receives melt water from glaciers in the valleys north of Chisagang Ri peak, north of Bhutan in Tibet (China).

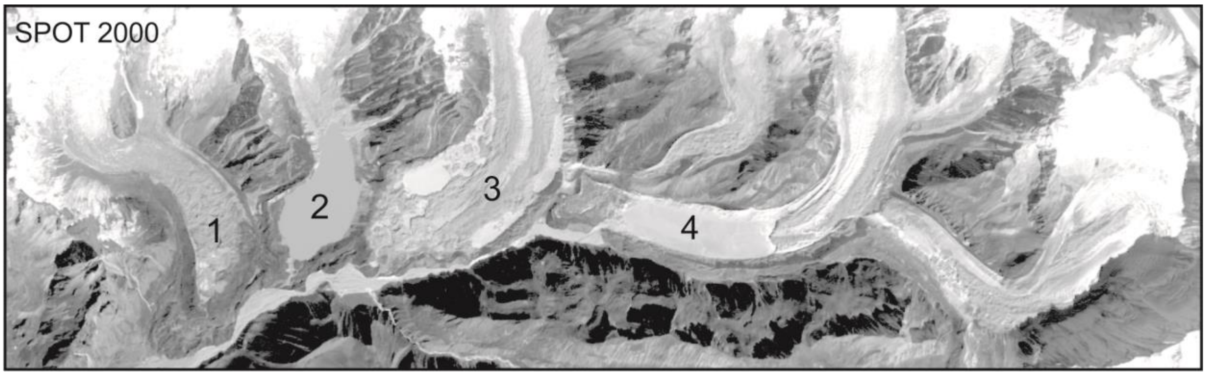

Figure 3: The main glaciers and lakes in the Lunana area of northern Bhutan: (1) Bechung Glacier, (2) Raphstreng Tsho, (3) Thorthormi Glacier, and (4) Luggye Tsho, which burst in 1994.

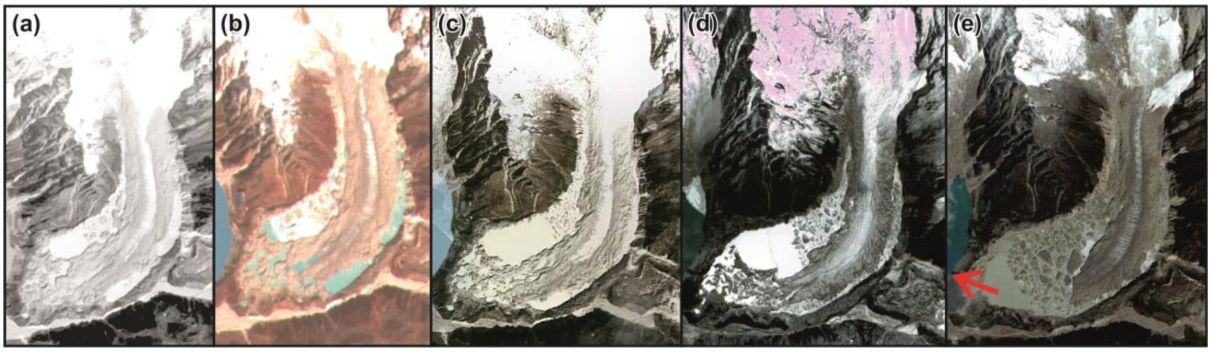

Figure 4: Time series of satellite images showing the disintegration of Thorthormi Glacier tongue and the growth of Thorthormi Tsho in (a) 2000 (SPOT); 2002 (ASTER); (c) 2008; (d) 2011, and (e) 2012. The most probable breach point is indicated by the solid red arrow in (e). Images (c) to (e) are courtesy of GoogleEarth, data © Mapabc.com US Dept of State Geographer/Cnes/SPOT image for image (c) and © Digital Globe for images (d) and (e).

4.3 India

There are an estimated 9,575 glaciers in the Indian Himal (Raina and Srivastava, 2008), the vast majority of which have never been investigated, although there has been a programme to design a helicopter-borne multi-sensor glacier mapping system (Reynolds, 2013). It is not known in any detail how many glacial lakes there are or where they are as they have not been mapped. There has been no comprehensive glacial hazard assessment across the entire Indian Himal.

There are a number of significant glacial lakes in Sikkim (as well as debris-covered glaciers with the propensity to form large glacial lakes (by virtue of low surface gradients). Images of a former glacial lake that has drained by a GLOF in Sikkim and of a current glacial lake in Himachal Pradesh are shown in Figure 5. Glaciers in Himachal Pradesh and Uttarakhand show early indications that lakes will develop in the future on some more-flat-lying glaciers, including within catchments where major hydropower schemes are proposed or are under construction.

4.4 Pakistan

In 1929, Chong Khumdan Glacier on the Upper Shyok River, produced a flood with a peak flow rate in excess of 40,000 m³/s following an ice dam lake outburst. A total volume of ~1.5 km³ was discharged in two days. Over fifty outburst events have been identified within the Upper Indus region between 1833 and 2010 with many in the early 20th century arising from ice dam failures and in the last decade or so increasingly from GLOFs. The Khurdopin Glacier (Figure 6) surged in the late 1990s leading to the formation of a temporary ice dam, which was overtopped by the impounded reservoir on 28th May and breached on the 10th June. The Hunza valley was affected by a GLOF in 2008, which caused significant local damage to downstream communities. Also of great local significance is the formation of very large landslide-dammed lakes, one of which (Gojal lake) formed in January 2010 near Attabad in the Hunza Valley. On 4th January 2010 a massive landslide occurred, killing 20 people, and blocking the Hunza River for five months. The lake that formed reached 21 km long and over 100 m deep and inundated over 21 km of the arterial Karakoram Highway, the vital communication link between many communities in the area as well as regionally. This event highlights the sudden onset-long impact nature of such an event and is equally pertinent whether the cause is a landslide dam failure, ice dam failure or a GLOF. Given that such events are known to occur within the Upper Indus region any hydropower project must take such events into account for each stage of a project's development.

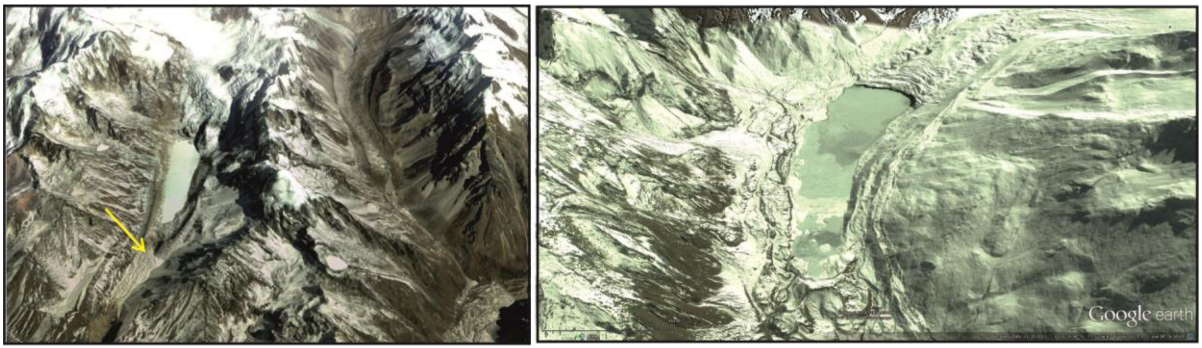

Figure 5: (*Left*) A glacial lake in Sikkim, India, that shows evidence of having breached (arrow). [Image courtesy of Google Earth; data ©Mapabc.com and US Dept of State Geographer.] (*Right*) Glacial lake in Himachal Pradesh. [Image courtesy of Google Earth; data ©DigitalGlobe and ©Cnes/SPOT Image.]

Figure 6: Landsat-5 image (August 1998) showing Yazghil and Khurdipin glaciers, the latter of which surged in 2000 and blocked the Shimshall River by forming an ice dam.

5. Risk management for hydropower projects

There are three strategies to managing glacially-derived floods, be they from moraine-dammed lakes or from ice dam failures, namely: (a) resistance; (b) deflection, and (c) avoidance. In the first case, the design and construction programme of the structures should take into account the range of flood types and magnitudes and ensures that the structures are capable of resisting such inundation to defined levels of damage. In the second, the scale of possible flood events may be too large to be able to engineer resistant structures and it becomes necessary to build structures upstream between the hydropower facility and the flood source to divert the main flood away from vulnerable or key structures or to dissipate its energy. Such diversionary structures might include weirs and diversion dams. The third case is where neither of the first two are practical and where the only solution is to remove the water from the source such that a flood never occurs or only occurs with reduced capacity, such that the resultant flood can be dealt with by either (a) or (b) or both. However, each of these scenarios requires that the likely nature of the potential flood has been defined to within acceptable and realistic limits of uncertainty. To this end, the limitations of GLOF modelling discussed above are germane. It is also important to monitor upstream hazards on a regular basis as they will change in response to changing climate and to update appropriate contingency response plans accordingly.

Where mitigation engineering works have been undertaken in the Himalayas they comprise: the installation of siphons as a first stage water level draw-down method (as at Tsho Rolpa, Nepal, 1995-99); excavation of a shallow channel using manual labour (as at Raphstreng Tsho in 1996-98 and more recently at Thorthormi Tsho in Bhutan) and by using mechanical excavators to form a 100-m long open channel controlled by sluice gates (as at Tsho Rolpa in Nepal in 1999-2000; Figure 1). The styles of mitigation works that have been undertaken in Peru, where such engineering projects have been undertaken since 1941 for both civil defence and hydropower projects (Reynolds, 1998b), have been used to guide the initial remediation schemes proposed at Tsho Rolpa, and illustrate some of the methods that might prove useful in the Himalayas.

Whereas GLOFs, once they have occurred at a particular glacial lake system, are very unlikely to recur, given that the ponding dam will have been breached, glaciers in the Karakoram, for example may undergo repeated phases of surging (Quincey and Luckman, 2013). Therefore, once a glacier has surged, it cannot be assumed that it will not do so again. While the return periods of glacier surges in the Karakoram are almost entirely unknown, the Khurdopin Glacier, for example, surged during the late-1970s. The same glacier surged again in the late 1990s, indicating a return period of 20 years (Quincey and Luckman, 2013). Indeed, the surge formed an ice dam that blocked the Shimshall River in May 2000 until it failed through overtopping on 10th June 2000. This suggests that if glaciers exhibiting surge-type behaviour are present within the catchment of a hydropower scheme whose design life is 50 years, there is a significant probability that the same glaciers will surge again during that period, perhaps more than once.

It is possible that glacial lakes that did not exist during the feasibility study period may develop post-construction and their hazards may become more significant with time, hence the need for regular monitoring. Even after a glacial lake has been mitigated, there is still a need to monitor the local mountain environment in case new processes start to occur such as induced by thawing permafrost at high altitude and changes to the thermal regimes of particularly high-altitude cold-based glaciers currently frozen to their bases; in time as there thermal regime transitions to more wet-based temperate conditions, such steep glaciers could start to slide and generate large slab failure ice avalanches.

6. Conclusions

With increases in global temperatures with changing climate highly likely, coupled with reductions in snow fall, and increased thawing of permafrost, including at high altitude, the style and scale of mountain and, in particular, glacial hazards are likely to change over time. Many glaciers in the Himalayas, from northwest India through Nepal, Sikkim and through to the east of Bhutan, are retreating significantly with some in states of disintegration. This recession is coupled with increasing volumes of melt water being stored as glacial lakes, dammed behind moraines. When such a glacial lake system reaches a critical point of marginal stability, an external trigger, such as a rock/ice avalanche, sudden influx of water from an upstream glacial lake, or potentially an earthquake, can cause the moraine dam to fail, thereby releasing increasingly large volumes of water as outburst floods.

Most of the glaciers in the Karakoram are stable, advancing and, in many cases, surging. Some major glaciers exhibit repeated surges recurring after an interval of 20 years while others undergo pulses of surges over perhaps as long as a ten-year period. A surging glacier tongue can flow into and block a major river, causing very large volumes of water to accumulate over a short period of time (a few weeks). The causes of surge behaviour are still unknown. The Chong Khumdan Glacier ice dam failed in 1929 with a peak flow in excess of 40,000 m^3/s. The Khurdopin Glacier has repeatedly surged, with its most recent activity peaking in 2000. Run-out distances in excess of 200 km for Himalayan GLOFs and over 1,200 km for outbursts from ice dam collapses in the Upper Indus catchment have been reported.

Given the significant existing and planned capacity for hydropower in the Hindu Kush, Karakoram and Himalayas, it is recommended that the glacial hazards in upstream catchments are properly assessed and then reviewed and monitored regularly, preferably every five years.

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