The application of geosciences to glacial hazard management

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Abstract
Climate change is at the forefront of media attention, with ‘carbon footprints’, greenhouse gases, melting of ice caps, etc., now recognised widely by the public at large. School students, as perceptive as they are, are also acutely aware of ‘global warming’. But when it comes to the curriculum there often is a huge gap between what is being taught and the application in the ‘real world’. Without an obvious use for the material where is the motivation to learn? The following is derived from an invited presentation by Professor John M. Reynolds to the ESTA Conference at Liverpool John Moores University on 13th September 2008.

Introduction
I have had the opportunity to present many talks to school students, mostly in the 16-18 years age bracket. I have found that when exposed to the example of glacial hazards they can immediately see the use of learning science and how it can be used to help people less fortunate than themselves. They become enthused. What is more, the activity of obtaining the scientific information can appear a bit Indiana Jones-ish, with travelling to remote parts of the world, jumping in and out of small helicopters, living in tents for weeks on end, trekking with yaks, and so on. Science not only can be fun but can also be tremendously exciting, adventurous and, dare I say it in these Health and Safety conscious days, even a bit dangerous! It was all of these things that excited me at school and continue to do so.

What are glacial hazards?
A glacial hazard is defined as a glacier-related characteristic or process that may potentially lead to loss of human life, disruption to human activity or damage to man-made structures (Reynolds, 1992). As climate changes the majority of glaciers around the world are shrinking in size. As the ice melts and the glacier tongues retreat up valley, lakes are formed, dammed by terminal moraines (Figures 1 and 2). Sometimes, the moraine may contain blocks of stagnant glacier ice, stranded remnants of the retreating ice tongue. As these blocks melt, they cause subsidence within the moraine, lowering the freeboard of the dam (the height between the top of the dam and the lake level), until the lake can drain through the subsided portion. The flowing water causes erosion on the outer flank of the moraine weakening it until the weight of water behind it causes the dam to fail, often spectacularly and explosively, leaving a huge breach (Figure 3). Moraine failure can also be caused

Figure 1 Schematic illustrating the causes of Glacial Lake Outburst Floods. The arrows indicate processes that form glacial hazards, from ice avalanches through to displacement waves from calving glacier tongues. © RGSL (2002-2009)

Figure 2 Imja Tsho (lake) near Mount Everest in Nepal with its moraine complex comprising debris-covered stagnant ice. The main glacier can be seen at the right hand side. © RGSL (2002-2009)
by the dam being overtopped by a wave generated by huge amounts of rock and/or ice avalanching or sliding into the lake from steep hill slopes adjacent to a lake (Richardson and Reynolds, 2000).

One of the largest examples of this I have seen personally was at Safuna in the Cordillera Blanca, Peru [8° 50’ 33.28” S, 77° 37’ 09.42” W, Figure 4]. In April 2002 a massive landslide collapsed onto and over a glacier tongue and into a lake below, displacing about half of the volume of the lake into a wave between 85 and 110 m high (Hubbard et al., 2005). This rushed up the moraine whereupon part of it became airborne before falling onto the outer flank of the dam where it washed much of the surface away. Some of the displacement wave then flowed back into the lake before resurfing back onto and over the moraine. The wave repeated this back and forth action as much as ten times, with each run up the moraine being less powerful than preceding waves as it began to run out of energy. The same effect can be replicated by displacing water in a bath tub. Thankfully the moraine dam survived, albeit greatly weakened by this event. However, a similar amount of rock is likely to collapse in another equally large landslide into the lake in the future ...!

When a moraine dam fails, what is called a Glacial Lake Outburst Flood (GLOF) ensues, with peak discharges up to 6,500-10,000 m3/s and durations at lower flow rates for 12-36 hours, depending upon the reservoir of water being drained. Typical monsoon flow rates, for comparison, may be of the order of several hundred cubic metres of water per second. The distance along which damage occurs is often tens if not hundreds of kilometres. For example, when Luggye Tsho [28° 05’ 34.09” N, 90° 17’ 52.16” E] in Bhutan burst in 1994, the flood wave travelled 86 km to Punakha where 19 people were killed, before flowing a further 118 km to the Bhutanese-Indian border where it was known that the flood wave was at least 2.4m high. The wave could have been higher than this but the flood hydrograph instrument was destroyed by the flood and 2.4m was its maximum value. The wave went on into northern India before dissipating – a total distance in excess of 210km.

The Himalayas have seen many such GLOFs although thankfully the death toll has been relatively low and much smaller than that in Peru, where over 32,000 people have been killed by glacial floods during the 20th century. Sometimes the economic effects can be more devastating than the physical damage. For example, in 2002, a glacially-derived flood wave and debris flow blocked the Vilcanota River, downstream from Machu Picchu, forming a 70m high temporary dam. The blocked river formed a large reservoir that in turn submerged an underground powerhouse of a nearby hydro-electric power station, effectively putting it out of operation. It took three years to rebuild the plant and restore power, and the damage, rebuilding costs and loss of power generation cost $200 million; however, no-one was injured.

Glacial hazard assessment – regional

One of the most effective methods of assessing glacial hazards is to use optical remote sensing – images from satellites – that can be viewed in both 2D and 3D. They provide an increasingly sophisticated range of techniques by which lakes and their associated environments can be viewed, mapped and classified (Quincey et al., 2005). They provide a very rapid means of measuring the location, shape and extent of glaciers and where glacial lakes are present. Indeed, it is now possible to determine where supra-glacial lakes are most likely to form in the future on debris-covered glaciers in the Himalayas. Digital Elevation Models (DEMs) created by using stereo satellite pictures can be used to provide the topography of the ground. From this information it is possible to identify areas on a glacier where the surface gradient is less than 2°. These
areas also tend to coincide with parts of the glacier that are undergoing stagnation and are no longer flowing downhill fast enough to permit crevasses from opening and closing (Quincey et al., 2007). Ponds that form on the glacier’s surface where ablation exceeds accumulation (negative mass balance) then coalesce, gradually developing into the large supra-glacial lakes like that shown in Figure 2. Research I undertook in Bhutan in 1998 (Reynolds, 2000) demonstrated that these lakes only form where the surface gradient is less than 2°. This now provides a means of identifying perhaps two to three decades ahead of time where significant glacial lakes are most likely to develop.

Information about the rate of ice flow can be obtained by comparing images of the glaciers taken at different times, often several years apart. Features identified on the older picture can be identified on later images and their new position determined. In addition, satellite radar interferometry can be used to measure directly the rate of flow and is sufficiently sensitive to be able to measure flow speeds as slow as 2 cm per day (Quincey et al., 2007).

From these various measurements from satellite images, a wide variety of information can be gathered. This includes details for the area of the lake, the nature of the ice tongue where it flows into the lake, the freeboard and nature of the moraine dam and the general morphology of the terminal moraine complex. This includes trying to determine whether or not the dam contains stagnant glacier ice. Often the surface geomorphological features (landforms) are characteristic but sometimes they are not and the only way of telling is by surface investigations. Multi-Criteria Analysis is now used to link various factors together in order to derive an overall hazard score. This links such parameters as lake volume, freeboard, whether the moraine is cored with ice, and the nature of drainage from the lake (all known as threshold parameters) with potential for sudden events, such as calving from the glacier tongue, and rock and/or ice avalanches (which can create displacement waves), and drainage on and within the mother glacier itself (all know as trigger parameters). The higher the score on both of these types of parameters, the higher the likelihood of the lake posing a significant hazard. Using satellite imagery, it is possible to rank a large number of glacial lakes within a river catchment according to the respective hazard score. This helps government agencies prioritise their attention to those lakes that are determined objectively to pose the highest threat.

Glacial hazard assessment – field expeditions

Using satellite imagery to focus attention to the most hazardous lakes enables field expeditions to be undertaken to investigate those issues left unresolved by the remote sensing. Sometimes it is possible to drive to remote sites but at other times it requires flying by helicopter and/or trekking on foot for many days with yaks (in the Himalayas) or going on horseback (in the Andes). Accommodation is typically in tents with very rudimentary facilities. But then there is nothing quite like opening up the flap of one’s tent and watching the sun rise over Mount Everest!

Major expeditions involving many scientists are extremely expensive but can yield huge amounts of key information that are fundamental in the assessment of the hazard of a particular lake. The types of disciplines used include glacial geomorphology, glacial and engineering geology, geotechnical engineering, structural glaciology, geophysics, and topographic surveying. In essence, what is trying to be achieved by these techniques is a map of the surface landforms and processes and an indication of what is beneath the surface (using geophysical methods). Ideally, the combined use of these techniques leads to the formation of a 3D ground model that can then serve as the basis of detailed assessment of the local hazards and essential information required in the case there is an opportunity for physical remediation, such as has happened at Tsho Rolpa in Nepal [27° 52’ 11.00” N, 86° 27’ 55.00” E] between 1996 and 2000.

The ground investigations use methods that are based on scientific principles that are commonly taught within schools in physics, mathematics, and physical geography. For example, the geophysical methods most commonly used now include Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR). ERT uses Ohm’s Law as its fundamental basis so that by injecting a current into

![Figure 5 (a) Ground Penetrating Radar section, and (b) the corresponding Electrical Resistivity Tomography section showing the resistive anomalies associated with massive glacier ice beneath a veneer of debris. The lateral moraine is prominent at the right hand side of each graphic. © RGSL (2002-2009)](image)
the ground through two steel electrodes and measuring the ensuing voltage between another pair of steel electrodes an electrical resistance can be measured. By knowing the geometry of the deployment of the electrodes an electrical resistivity can be calculated. Incrementally moving the four electrodes along a profile and successively increasing the separation between the electrodes enables a 2D electrical resistivity ‘image’ of the subsurface to be produced (Figure 5a). Similarly, the transmission of radiowaves at a frequency of 100 MHz from a pair of antennae on the ground surface and recording the time it takes for those signals to be reflected back produces a 2D radargram image of the subsurface (Figure 5b). Given a radiowave velocity (V) through the local material, it is possible to turn the two-way travel time (t) into an approximate depth (d) using $d = Vt/2$.

Where stagnant glacier ice is present in a moraine it can be identified by its high resistivity in comparison with wet, loose, morainic material. The examples shown in Figure 5 are for a coincident profile across part of the terminal moraine complex at Imja Tsho, Nepal [27° 54’ 02.00” N, 86° 55’ 00.00” E] (Reynolds, 2006). Details of these two methods can be found on two Technical Summary Sheets available as PDFs from www.geologyuk.com; the principles have also been provided in significant detail by Reynolds (1997).

**Mitigation methods**

Having identified that a glacial lake poses a significant hazard, it might be possible both financially and physically to remediate it, i.e. reduce the degree of hazard by undertaking some engineering works. This has been done mostly successfully in Peru since 1941 but the first remediation in the Himalayas was at Tsho Rolpa in 1995 when siphons were first installed. These enable water to be drained from the lake without the need for pumps and demonstrated that the method would work at 4,500 m elevation. It had been tried successfully in Peru in the late 1980s. However, the rate of drainage was insufficient to draw down the lake level in the time required so a more ambitious plan was hatched. This involved the excavation and construction of a 100m long open spillway (Figure 6) whose flow was controlled by sluice gates (Rana et al., 2000). Every piece of machinery and equipment had to be airlifted slung under a helicopter as the nearest road was more than 40km away. This included dismantling excavators, flying them to site in many loads, and then rebuilding them on site, which was no mean feat. The excavators and dumper trucks are now housed in a specially constructed garage on site in readiness for the next stage of remediation, if it ever happens. The rationale behind this scheme was to provide protection not only for the several thousands of people who lived along the river valley downstream but also to safeguard a new hydro-electric power installation. It had been estimated by the managers of the hydro-plant that should Tsho Rolpa fail and a GLOF strike it could generate $24 million in damage, whereas to spend $3 million on the remediation was the most expedient approach. The work took 18 months over two summers to complete (1999-2000) and remains the largest remediation scheme of its type worldwide.

In order to help justify the expense, it had also been necessary to examine the downstream vulnerability, and this required an assessment of the demographics of the local communities. This is an area pertinent to human geography, sociology and economics. I would go a stage further and say that it is also necessary to consider the psychology of the local communities too as the perception of the hazard may not even exist or the locals may believe fatalistically that if a GLOF occurs and they are killed it is their ‘karma’ or fate. What these projects have demonstrated is that despite the magnitude of the problems, literally, it is possible to manage them either directly through mitigation measures, or indirectly including their effect in the structure’s design and removing or protecting vulnerable structures. In Bhutan, the government relocated an entire community to a safer location as its response to possible future inundation of the village.

![Figure 6 The open channel nearing completion at Tsho Rolpa. The sluice gate structure is immediately behind the building adjacent to the canal. © RGSL (2002-2009)](Image)
Conclusions

Glacial hazards are one of the more obvious and direct adverse effects of current climate change. Those most vulnerable live in remote communities and are amongst the poorest on Earth. The assessment and mitigation of glacial hazards provide opportunities for Earth Scientists to play an important role in the protection and well being of those remote communities. It enables those formerly ‘at risk’ communities to plan their own future better knowing that their physical safety is assured as far as it is possible. This helps the local economy and encourages local investment to enable those communities to help themselves. Conceptually, it is also easy for students to understand both the physical and socio-economic problems and the range of the solutions required. It also provides the applications of those educational subjects that may often be perceived as boring and dull when in fact they can have such huge societal benefits and help to address one of the many issues related to climate change – science with a purpose!

Notes: I have provided latitudes and longitudes for key locations mentioned in the text so that these may be entered into the search box in GoogleEarth. Students can then navigate to these locations and view in colour the lakes/sites mentioned using satellite images, and can rotate the perspectives themselves to obtain a 3D view that almost looks as it would if seen from a helicopter. Copies of papers mentioned in the text are also available as PDFs online via our website (www.geologyuk.com) so teachers can read the details behind each example. Furthermore, annotated colour versions of pictures used here, plus some of those from some of the papers mentioned can be obtained online from A Vision of Nature Ltd (www.avisionofnature.co.uk) in a format suitable for use in MS PowerPoint™.

Readers are also referred to the teaching aid ‘Dam burst danger’ (www.earthlearningidea.com) developed by Peter Kennett to demonstrate the effects of melting ice blocks within a moraine dam.

References


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