On the need to integrate Disaster Risk Management within the hydropower sector

John M. Reynolds
Reynolds International Ltd
Suite 2, Broncoed House
Broncoed Business Park
Wrexham Road
Mold
Flintshire
CH7 1HP
United Kingdom

Introduction

Geologically young and dynamically-active high mountain regions such as the Himalayas experience high levels of tectonic seismicity. Moderate to large magnitude earthquakes can trigger rock and ice avalanches as well as multiple landslides. Heavy rainfall during the summer monsoon, compounded by cloudbursts, can also lead to landslides, mudslides and debris flows, all of which can wreak havoc on downstream communities and infrastructure. Major landslides can block rivers to form landslide dams impounding potentially large volumes of water upstream; failure of such dams can result in Landslide Dam Outburst Floods (LDOFs). It is possible that changing climate is altering precipitation patterns as well as resulting in rising temperatures, especially within the High Himalayas. Temperatures appear to be rising faster at higher altitudes than at lower elevations. This is affecting glaciers and snowfields and melt-water run-off, which in turn impacts on river flow volumes, both during peak flood and low-flow periods. Thawing high-altitude permafrost is thought to result in more destabilisation of steep mountain flanks, which gives rise to catastrophic mass movement as seen by landslide activity. Mass-movements from mountain flank destabilisation can produce rock and ice avalanches that can impact into glacial lakes resulting in potentially highly-damaging Glacial Lake Outburst Floods (GLOFs).

Across the Himalaya-Hindu Kush-Karakoram mountain ranges, destabilisation of hillslopes through landslides and mudslides in conjunction with heavy rainfall, can massively increase the sediment load in rivers. In extreme hydro-meteorological events, sediment fluxes totalling several years' worth of sediment volume can be disgorged in a matter of days, overwhelming hydropower facilities downstream. Furthermore, once slopes have been undercut and destabilised, they provide an ongoing source of elevated sediment load (suspended and bed-load) for years afterwards, resulting in substantially increased abrasion of turbine blades, for instance. For major storage schemes, accelerated influx of sediment in excess of design values through extreme hydro-meteorological events can result in substantial reduction in reservoir volumes, reduce generation efficiency and increase maintenance costs.

There have been a number of disasters that have affected the hydropower sector across the Himalayas in recent years. Most notable are the cloudburst-induced flooding in Uttarakhand, northern India, in June 2013; the landslide-dam event on the Sun Kosi River in Nepal in August 2014; and the consequences of the Gorkha and Dolakha earthquakes in central Nepal in April and May 2015. Events such as these have highlighted how ineffectively Disaster Risk Management (DRM) has been integrated into the hydropower sector in these countries.

Since the adoption of the *Hyogo Framework for Action* in 2005 significant progress has been made in reducing disaster risks at a variety of levels. Following the Great East Japan earthquake and tsunami of 2011, there has been more focus on mainstreaming Disaster Risk Management (The World Bank, 2012). In March 2015 *The Sendai Framework for Disaster Risk Reduction 2015-2030* was adopted at the Third United Nations World Conference on Disaster Risk Reduction (UNISDR, 2015). Following these initiatives the need to increase DRM and resilience, particularly within the hydropower sector, has been highlighted. Examples of disasters affecting the hydropower sector in the Himalayan Region and issues arising from the prior assessment of geohazards and disaster management are discussed and recommendations made.

1. Recent disasters in the Himalayas that have affected hydropower installations

In June 2013 in Uttarakhand in Northern India, over 450 mm of rain fell in 60 hours triggering landslides and debris flows resulting in the loss of over 5,000 lives and massive damage over a very wide area. The sluice gates of the 400 MW Vishnuprayag HEP scheme on the Alaknanda River were largely destroyed (Figure 1). The event transported more than the total annual sediment flux of the catchment through this river system during the floods over four days, significantly modifying the sediment load characteristics of this river.

Figure 1: Vishnuprayag Hydropower Plant sluice gates being inundated and destroyed by the floods in Uttarakhand, northern India, in June 2013. (Image courtesy of www.thehindubusinessline.com).

On 2nd August 2014, a major landslide crashed down onto a village and blocked the Sun Kosi River in Sindhupalchowk District, about 60 km from Kathmandu in Nepal (Figure 2). The landslide dam impounded the river, the level of which rose rapidly and formed a large lake upstream. Several villages situated along the river were evacuated. The dam was artificially breached but the ensuing flood caused significant damage downstream. In addition to killing over 150 people, the event resulted in damage to 67 MW of hydropower infrastructure, reducing the country's installed capacity by 10% and increasing load-shedding in Kathmandu by 1½ hrs per day.

Figure 2: The landslide and the dam it formed across the Sun Kosi River, August 2014. The 10 MW Sun Kosi HEP sluice gate structure can be seen in the bottom centre of the picture. (Image courtesy of www.heraldsun.au).

It was reported that had the debris been cleared at the sluice gates before discharging the water in the landslide lake not all of the gates would have been blocked. As four out of the six sluice gates were blocked following the landslide dam discharge, the river has been eroding the river bank at the northern side of the dam gates threatening further damage to the structures. It was estimated in September 2014 that the project would be generating again at full capacity within a year.

From examination of available satellite imagery of the Sun Kosi landslide site from as early as March 2004 there are signs of early stage slope movement that can be seen to have developed further by 6th October 2012. An upper backscarp continued to develop through into February 2013 prior to total failure on the 2nd August 2014. A sequence of images extracted from Google earth scenes is shown in Figure 3. The earlier slope movements appear to have been surficial failures with the fatal event being initiated further upslope and being deeper seated. The question has to be asked – why were these early signs of slope failure not identified at the time and reported so that the hillside could have been investigated, especially given the proximity of the 43-year old 10 MW Sun Kosi HEP plant and local communities? This highlights a dilemma for the hydropower industry. How far from a particular HEP site do site-specific responsibilities extend up- (and down-)stream? Is landslide potential a responsibility of the Nepalese Government to map and determine (*e.g.* Department of Geology and Mines)? If so, how is the information about risk shared with communities and HEP plant operators and under which national policy/ies does this communication coordination fall, if any?

Within this landscape of a tectonically and geologically active mountain environment, communities have developed and a growing number of increasingly large hydropower projects are being developed. Yet it is clear that there is no co-ordinated and joined-up policy in which the hydropower sector can operate with clearly demarcated lines of responsibility. Given the age of the Sun Kosi HEP plant, that the landslide occurred more than four decades after construction it could be argued that the risk of landslides at this location was previously unknown. However, there are records of geotechnical studies being undertaken on slopes associated with the project site, such as on the southern side of the valley and that it had been long known that parts of the site were susceptible to such events (Pokharel, 2001). However, it is clear that the northern hillside began to become unstable at least a decade before total failure occurred. Should this, therefore, have formed part of the ongoing monitoring programme of the HEP operators? Or was it that the location of the landslide lay outside of the site boundaries and was therefore someone else's responsibility? This discussion is in no sense any attempt at trying to apportion blame to any party. However, it serves to highlight the issues affecting the hydropower sector.

Figure 3: The development of the Sun Koshi landslide between (*left*) 31st October 2009; (*middle*) 13th February 2013; and (*right*) 10th August 2014, eight days after the disaster. The location of the Sun Kosi HEP sluice gate structure can be seen across the river in the lower left of each image. (Images extracted from Google earth – © DigitalGlobe).

On the 25th April 2015, a 7.8-magnitude earthquake struck central Nepal triggering thousands of landslides (Collins and Jibson, 2015; Reynolds, 2015). This was followed by many aftershocks and also by another large earthquake, magnitude 7.2, in Dolakha District on the 12th May 2015. These earthquakes and the ensuing landslides and rock falls resulted in significant damage to both operational hydropower facilities and also to ones under construction, especially that at Lamabagar, the Upper Tamakosi HEP scheme. In addition to damage at the plant site itself, the only access road was badly damaged. In the 7-km long stretch of road immediately downstream of the plant, at least 27 landslides were mapped and zones of destabilised hillside were also identified. It is feared that these areas may have become reactivated during the 2015 monsoon.

One of the landslides south of Lamabagar HEP plant at Gongar Village, Dolakha District, is shown (viewed towards the south) in Figure 4 with the same area before and after the earthquake on the 25th April 2015. The access road built for the Upper Tama Kosi HEP project at Lamabagar can be seen to the west of the river. A set of large buildings (in the lower centre of the top picture) was almost completely buried by the landslide, which also blocked the access road.

The major earthquake sequence associated with the Gorkha and Dolakha earthquakes on 25th April and 12th May 2015 has prompted serious examination of the resilience of infrastructure and communities to such events. No less so is this relevant to the hydropower sector, which was severely impacted by these events and for which determination of the extent of damage and of the consequences is an ongoing process at the time of writing (August 2015). These events highlighted once more the level of general unpreparedness of the society and of the hydropower sector in Nepal.

2. Integrated consideration of geological and hydrological risks

From analysis of events such as these it is apparent that the hydropower sector in these high mountain environments is not sufficiently prepared for such disasters. It is evident that the consequences of extreme hydro-meteorological processes have not been considered adequately at the pre-feasibility, feasibility or design stages of the projects. Geotechnical Baseline Reports and Hydrological Risk Assessments have been undertaken separately and without considering the combined effects of both geology and hydro-meteorology. Furthermore, in Nepal, for instance, there is a policy vacuum and a lack of technical capacity with regard to considering possible disasters. This applies equally to the management of sediment as well as water within hydropower projects. Recent disasters in Nepal and India have highlighted the inadequacies both of government agencies and the hydropower sector in considering how Disaster Risk Management should be integrated at all stages in project planning and construction through to plant operation for the entire duration of any hydropower project.

Figure 4: The village of Gongar beside the Tama Kosi River, Dolakha District, Nepal, shown (*top*) before and (*bottom*) after the Gorkha earthquake of the 25th April 2015. (Oblique images derived from Google Earth imagery).

Table 1: Triggers and geographic scales of various flooding event types (after Reynolds, 2014).

Event trigger/process	**Consequences**	**Scale**
Earthquake	Landslides and Landslide-Dammed Outburst Floods	Regional depending on the magnitude of the earthquake; multiple river catchments, thousands of km^2.
Cloudburst or exceptionally prolonged heavy rainfall	Landslide-Dam and Glacial Lake Outburst Floods, river and surface-water floods, debris flows, mudslides	Regional depending on the volume and duration of precipitation; multiple river catchments, thousands of km^2.
Rock-/ice-avalanche	Landslide-Dam or Glacial Lake Outburst Flood	Single catchment, flood run-out distances hundreds of km.
Ice-dam failure^	Ice Dam Outburst Flood	Single catchment, flood run-out distances can exceed 1,400 km.

^Ice dam failures can occur when a glacier surges and the rapidly advancing ice mass blocks a river impounding a reservoir upstream. Hydrostatic jacking or mechanical collapse of the ice dam releases very large volumes of flood water with very high peak flow rates. These events have been known to occur in the Hindu Kush-Karakoram region.

In any, especially high, mountain environment it is essential to determine the types and likely scales of natural disasters and their typical causes. Examples of types of event triggers and processes, their consequences and scales are listed in Table 1. Some triggers of disasters, their types and possible causes are listed in Table 2. It is also essential to recognise that some geologically-related disasters may be caused by hydrological processes and vice versa and in combination, as illustrated in Figure 5.

Table 2: Triggers of disasters, their types and possible causes.

Event trigger/process	**Type**	**Possible causes**
Earthquakes	Geophysical	Tectonic activity
*Cloudbursts or exceptionally prolonged heavy rainfall^*	Hydro-meteorological	Atmospheric processes coupled with effects of climate change?
Rock-/ice-avalanches and landslides	Geomechanical	• Debuttressing of mountain flanks from retreat of glaciers^ • Retreat of glaciers^ • Thawing of high-altitude permafrost^ • Earthquakes • Heavy and prolonged rainfall
Debris flows, mudslides	Hydrological and geological	• Heavy and prolonged rainfall • Saturation of material
Ice-dam failures	Glacial dynamics	?Climate change but causes of surging glaciers remain poorly understood

Triggers and possible causes are not necessarily mutually exclusive! ^?Associated with changing climate.

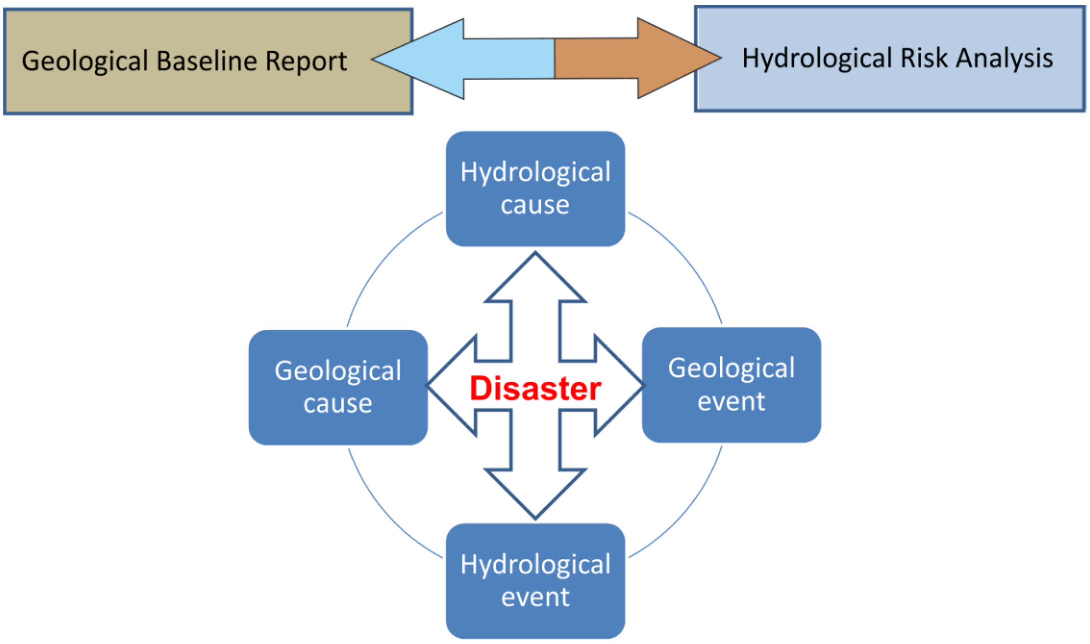

Figure 5: Inter-relationship between geological and hydrological causes and effects.

The current predominant model is for the Geological Baseline Report and the Hydrological Risk Analysis, for instance, to be undertaken separately, often by different organisations and without consideration of the other's work. This inevitably leads to disjointed and incomplete assessment of the risks. This has been discussed also by Blomfield and Plummer (2014). But there are also other considerations associated with these two types of risk analyses, which when produced independently of each other, are seldom considered, such as:

- Extent of geographical coverage and jurisdiction of geological and hydrological risk analyses
- Consideration of changes in physical systems and therefore risks with time (e.g. associated with climate change?)
- Responsibilities within HEP framework in relation to local, regional, national and international considerations
- Consideration of low-frequency high-impact events and their ongoing consequences
- Consideration of slow-impact, long-duration events and their ongoing implications (*e.g.* slow but large landslide mass movements)

- How and when within a project's development and operation plan should risks be considered?
- Implications for styles of contracts for hydropower developers

It is essential to remember that hydrological and geological processes are linked, not separate and therefore hazardous processes may have both geological and hydrological components (*e.g.* Selby, 1982; Tianchi *et al*., 2001). It is also essential that responses to disasters are coordinated so that a national resource of information is developed within the countries affected. At present such information if often dispersed across a myriad of organisations within and external to affected countries. Responsible agencies may not be able to have access to such information if there is no requirement to send copies of material to them, thereby depleting their technical capacity to learn from past events in order to inform better responses for future disasters. This is where the *policy* of DRM is especially important and why there must be coordinated responses into which the hydropower sector can contribute and, in turn, benefit.

3. Responses following the Gorkha and Dolakha earthquakes in Nepal in April and May 2015

Two major earthquakes occurred on the 25th April 2015 and on the 12th May 2015, known as the Gorkha and Dolakha Earthquake sequences, respectively, in Nepal. In addition to over 8,000 fatalities, many additional casualties and many more made homeless and/or displaced, there was significant damage done to particularly historical buildings and sites in Kathmandu Valley but also to existing hydropower facilities as well as to those currently under construction. Emergency inspection teams were despatched by helicopter and satellite imagery providers released high-resolution images within days of each event (*e.g.* Google Earth Crisis Maps imagery). Rapid assessment was undertaken using both helicopter observations and video recording and detailed assessment of satellite imagery (*e.g.* Collins and Jibson, 2015) to assess the damage from predominantly the first earthquake sequence. Fears were also expressed as to the status of two large glacial lakes, Tsho Rolpa in Rolwaling (Figure 6) and Imja Tsho in Solukhumbu. To address these concerns a status report (Reynolds, 2015) was produced from imagery acquired within days of the first earthquake. Both glacial lake systems were found not have been adversely affected by the earthquakes. For the case of Tsho Rolpa, which is regarded as Nepal's most hazardous glacial lake, this was important to know as any major flood from this lake could impact severely on the Tama Kosi River, the access road to the Upper Tama Kosi HEP project at Lamabagar, as well as low-level riverside communities and downstream hydropower installations (*e.g.* Khimti HEP project). The UNDP has recently estimated that there are $2 billion of assets at risk downstream of Tsho Rolpa, should there be a major flood from this lake.

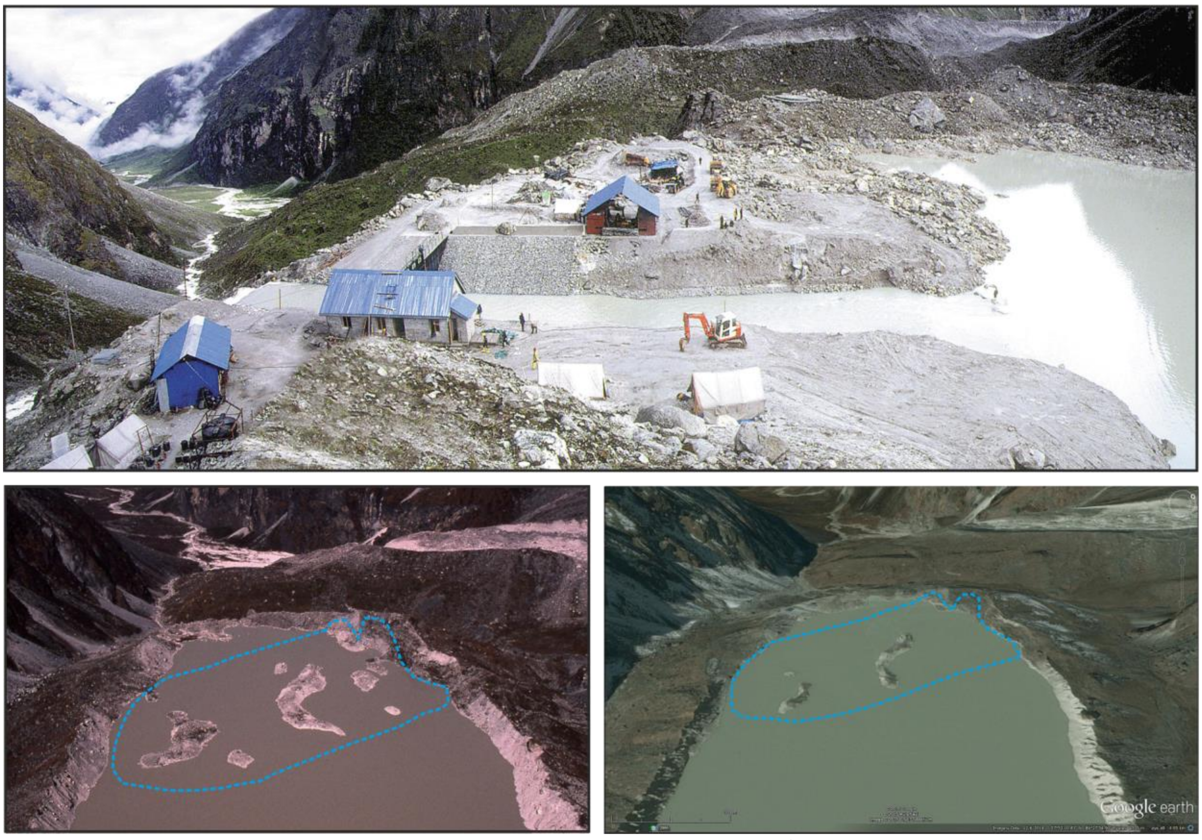

Figure 6: (*Top*) The open channel and outer sluice gate at the western end of Tsho Rolpa, Rolwaling, Nepal as seen in 2000. Islands of debris-covered ice atop a large submerged stagnant ice body, the approximate extent of which is indicated as seen in October 1998 (*Bottom, left*) and in December 2014 (*bottom, right*). Note the considerable reduction in extent of the islands between 1998 and 2014.

Whereas Imja Tsho is generally regarded as not posing a particular hazard downstream, Tsho Rolpa is thought to be Nepal's most hazardous glacial lake. It contains a substantial area of submerged stagnant ice that is grounded on the lake floor; the top of this debris-covered ice appears as debris-covered islands (Figure 6). Comparison of photographs and satellite imagery from October 1998 and December 2014 demonstrates the significant reduction in the number and sizes of the islands, despite the water level being 3.5 m lower since 2000 due to emergency interim remedial engineering works that were installed in 1999 and 2000 (Rana *et al.*, 2000). The remaining concern is not knowing if and when the submerged ice will become buoyant. If this occurs catastrophically it could destroy a significant part of the terminal moraine dam and initiate a major flood. Although recommendations to lower the lake level by 20 m relative to the level in 1994 were made over two decades ago, only the interim remediation has so far been installed. Further assessments of the status of the hazards at Tsho Rolpa are due to be undertaken in early October 2015 in order to inform the Rolwaling Diversion Tunnel Project for the Upper Tama Koshi HEP as well as the responsible government agency in Nepal.

4. Conclusions

It is evident from retrospective assessment of recent disasters in India and especially Nepal, as well as reviews of the current levels of hazard assessment and Disaster Risk Management in Pakistan and Bhutan that the hydropower sector across the South Asia Region is generally ill prepared to cope with catastrophic events. There is an over-reliance on existing but overly restricted Geological Baseline Reports and Hydrological Risk analyses. Sediment management analyses also do not give adequate consideration to the effects of disasters and other extreme events on hydropower installations and operational procedures. In addition, the hydropower sector is variably being required to act within an inadequate national policy climate. Issues like Glacial Lake Outburst Floods (GLOFs), while being mentioned in some national policies in Nepal, for example, do not provide sufficient detail on how such issues are to be managed but are limited to identifying whether there are GLOF hazards within a particular river catchment. This situation is exacerbated by inadequate national capacities to manage glacial and landslide hazards and overly complicated inter-agency relationships that inevitably do not function efficiently or in a coordinated way in the immediate aftermath of a major disaster.

It is recommended that the following are supported and implemented to improve the integration of DRM into not only the hydropower sector but other sectors too across the South Asia Region:

- Increased technical capacity within responsible national government agencies
- Significantly improved national hydro-meteorological and sedimentological sampling networks
- Improved and better coordinated national policies through which DRM can be implemented and enforced
- Better coordination between international bodies to reduce loss of inertia through geopolitical lassitude
- Greater requirements to integrate hazard assessments and risk analysis within the hydropower sector
- Improved contract arrangements to provide greater clarity on the jurisdiction of and responsibility for risk assessment and management throughout *all* stages of a hydropower project's life.

There is a range of initiatives currently being implemented across the South Asia Region by The World Bank (ADPC, 2010) and the UNDP, for example, in the realm of DRM and increasing resilience especially within the hydropower sector. However, some of the initiatives are being impeded by geopolitical sensibilities within the international community as well as by insufficient governance capability within national governments. These are major challenges for the international funding bodies and national governments as well as members of the hydropower sector. There is a need for improved dissemination of best practise throughout the sector so that more of the industry can benefit from the improvements that are being made.

Without significant improvement being achieved within the hydropower sector in making it more resilient to the impacts of natural disasters, it will continue to suffer significant financial losses from damaged or destroyed HEP installations through lack of appropriate preparedness.

References

ADPC. 2010. *Nepal Hazard Risk Assessment.* Asian Disaster Preparedness Center, Bangkok, Thailand.

Blomfield, A. and Plummer, J. 2014. The allocation and documentation of hydrological risk. *The International Journal of Hydropower & Dams*, **21**(5):94-108.

Collins, B.D. and Jibson, R.W. 2015. *Assessment of existing and potential landslide hazards resulting from the April 25th, 2015 Gorkha, Nepal earthquake sequence.* USGS Open File report 2015-1142.

Pokharel, G.S. 2001. Geotechnical study of unstable slopes: a case study at Sunkoshi power-house site, Central Nepal. *In:* Tianchi, L., Chalise, S.R. and Upreti, B.N. (eds). *Landslide hazard mitigation in the Hindu Kush-Himalayas*. International Centre for Integrated Mountain Development, Kathmandu, Nepal, pp. 231-247.

Rana, B., Shrestha, A.B., Reynolds, J.M., Aryal, R., Pokhrel, A.P. and Budhathoki, K.P. 2000. Hazard assessment of the Tsho Rolpa Glacier Lake and ongoing remediation measures. *Journal of the Nepal Geological Society*, **22**:563-570.

Reynolds, J.M. 2014. Natural Disaster Preparedness for hydropower projects in high mountain environments. *HYDRO 2014 Conference Proceedings, Cernobbio, Italy, 13th-15th October 2014*.

Reynolds, J.M. 2015. *Statement on the status of Tsho Rolpa and Imja Tsho after the Gorkha earthquake, Nepal, 25th April 2015*. Reynolds International Ltd Report, 20th May 2015.

Selby, M.J. 1982. *Hillslope materials & processes*. Oxford University Press, UK.

Tianchi, L., Chalise, S.R. and Upreti, B.N. 2001. *Landslide hazard mitigation in the Hindu Kush-Himalayas*. International Centre for Integrated Mountain Development, Kathmandu, Nepal. (Edited by Tianchi, L., Chalise, S.R. and Upreti, B.N.).

UNISDR. 2015. *Sendai Framework for Disaster Risk Reduction 2015-2030*. The United Nations Office for Disaster Risk Reduction, Geneva, Switzerland, March 2015.

The World Bank. 2012. *The Sendai Report: Managing Disaster Risks for a Resilient Future*. The World Bank, Washington D.C., USA, 61 pp.

The Author

Prof. John M. Reynolds holds a BSc in Geological Geophysics (Reading University) and a PhD in Glacio-geophysics (CNAA, Reading University and British Antarctic Survey, Cambridge). He has held posts at the British Antarctic Survey (Cambridge), Plymouth Polytechnic (now Plymouth University), and has run his own geological and geophysical consultancy company in Mold, NE Wales, UK, since 1994. He was appointed as an Honorary Professor at Aberystwyth University, Wales, in 2005. He is currently a Member of the Advisory Board of the Glacier and Permafrost Hazards in Mountains (GAPHAZ) Standing Group of the International Association of Cryospheric Sciences (IACS) and the International Permafrost Association (IPA). He has been involved in many projects relating to glacial hazards for civil defence, climate change and hydropower projects since the mid-1980s in Bhutan, Chile, India, Kyrgyzstan, Nepal, Pakistan, Peru, and Tajikistan. He is currently Managing Director of his specialist consultancy company Reynolds International Ltd, UK.

Reynolds International Ltd
Suite 2, Broncoed House. Broncoed Business Park, Wrexham Road, Mold, Flintshire, CH7 1HP, UK
Email: jmr@reynolds-initernational.co.uk