ICIMOD Research Report 2016/1

ICIMOD
FOR MOUNTAINS AND PEOPLE

The Impact of Nepal's 2015 Gorkha Earthquake-Induced Geohazards

skoll global threats fund

About ICIMOD

The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalisation and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. We support regional transboundary programmes through partnership with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream – now, and for the future.

ICIMOD gratefully acknowledges the support of its core donors:
the Governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland, and the United Kingdom.

Cover Photos: Award-winning cinematographer and climate change documentarian David Breashears captured images of Langtang village three years before the earthquake and days afterward.

The devastation shown in the second image was also observed by a raven. The raven is a complex character in world mythology. Ravens are generally seen as smart and mischievous birds and are commonly considered as messengers. According to ancient Hindu beliefs, ravens are the linkage between the living and the dead, and are considered to be ancestral beings. In Nepali Hindu culture, the raven and crow are worshipped on the first day of one of the most important festivals, Tihar. In Hindu mythology, Bhusunda was an old sage in the form of a crow. Bhusunda witnessed infinite cycles of dissolution and creation, and so he is a survivor and a figure of hope.

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The Impact of Nepal's 2015 Gorkha Earthquake-Induced Geohazards

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Contents

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Foreword

The Hindu Kush Himalayan (HKH) region is geologically fragile with unstable slope-land systems, and geohazards such as landslides and debris flows are common. The people of the region are very vulnerable to such natural hazards, a vulnerability compounded by the social conditions. Every year, geohazards resulting from a combination of natural conditions and human activity cause thousands of deaths and several billion US dollars in economic losses, hampering socioeconomic development and reducing progress in poverty reduction. The region also falls in a high seismic zone; earthquakes are a frequent phenomenon and cause significant loss of lives and property. In addition to their direct impact, earthquakes also induce additional geohazards such as landslides, which further contribute to the loss of lives and property. Nepal experienced a major earthquake on 25 April 2015, which devastated large parts of the country. The main shock of 25 April and several other aftershocks including that of 12 May caused the death of about 9,000 people, injury to 22,000, and loss and damage equivalent to USD 7 billion. Part of this was the direct result of shaking, while part resulted from the landslides, debris flows, and other geohazards that were unleashed.

Since its establishment in 1983, ICIMOD has dedicated considerable effort to finding ways to reduce the risk from natural hazards. We have held training courses, carried out hazard mapping and vulnerability assessments, fostered dialogue between stakeholders, and developed manuals to support capacity building. All of this has contributed towards reducing the physical and social vulnerability of the people of the HKH region. ICIMOD also has a history of supporting its regional member countries in times of natural disaster in every possible way.

Immediately after the earthquake on 25 April, ICIMOD joined hands with regional and international experts to map the positions of landslides and debris flows and where they had blocked river valleys. The information collected by the team was provided directly to the Government of Nepal to assist in relief efforts and was instrumental in the formation of a Geohazards Task Force by the government. Later, ICIMOD in collaboration with other experts undertook several studies including field surveys, airborne observations, and remote sensing mapping to assess the occurrence and impact of the geohazards induced by the earthquake and aftershocks, and where they had impacted on or posed a risk to housing and infrastructure, had cut off communications by blocking roads and trails, posed potential problems due to blocking of river valleys, or had led to or increased the risk of glacial lake outburst floods (GLOFs). This publication presents the results of this work together with findings from several other related studies. We hope that these findings and the recommendations drawn from them will help policy and decision makers in Nepal and other regional member countries in their efforts to prepare for geohazards and improve geohazard management.

David J Molden, PhD
Director General

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ICIMOD gratefully acknowledges the contributions made by the international volunteer group in mapping the landslides immediately after the earthquake. Special thanks go to the various agencies and individuals who provided satellite images, photos, and information during the study, and to NASA's SERVIR Applied Science programme for its support.

We would like to thank the many colleagues in ICIMOD who contributed to the preparation of this report. In particular, we would like to extend our sincere thanks to David Molden, Director General, and Eklabya Sharma, Director Programme Operations, for providing the opportunity to work on this project and for their valuable suggestions.

We are very grateful to our consultant editor A Beatrice Murray and to Amy Sellmyer, Dharma R Maharjan, and Asha Kaji Thaku from the ICIMOD editorial and production team for their support in the production process. Lastly we would like to acknowledge all members of ICIMOD's Publication and Outreach Committee (POUT).

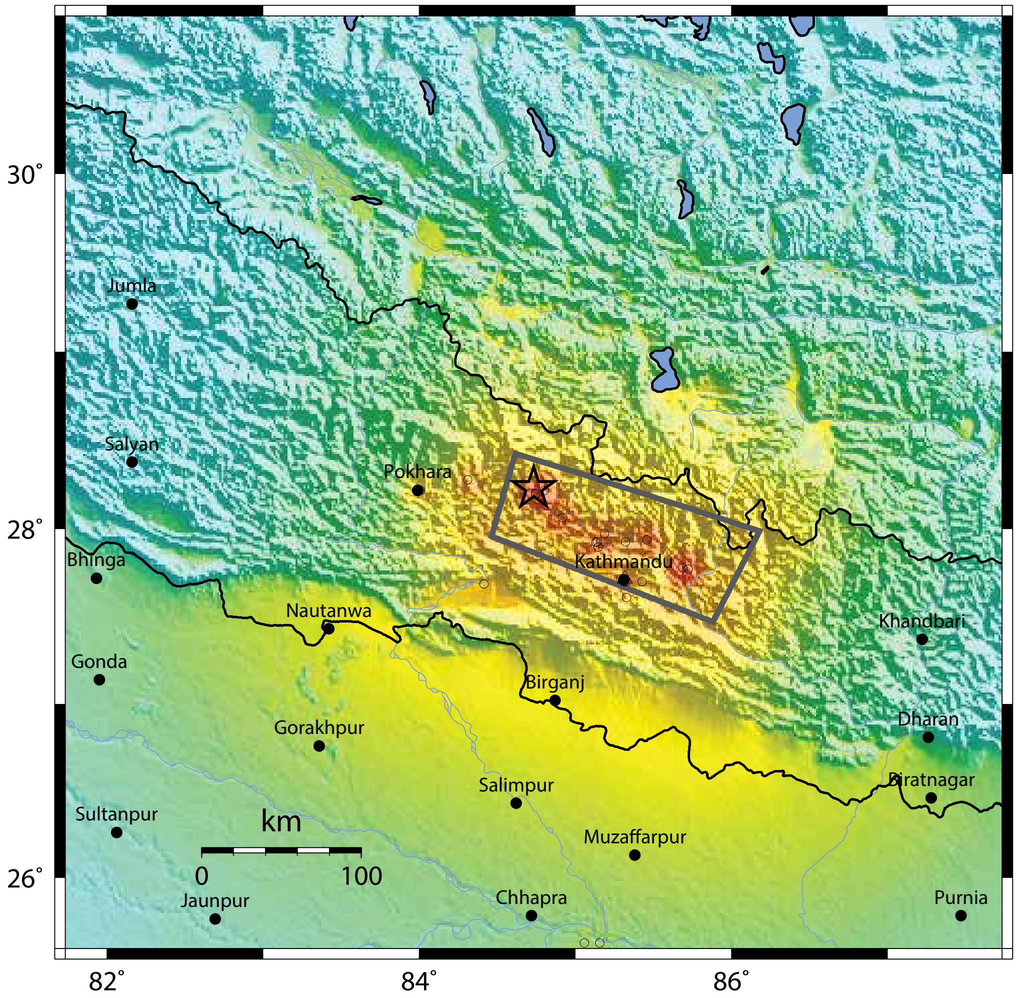
Note: All monetary values in this publication were originally compiled in Nepali rupees (NPR) and converted to USD at the rate current in April 2015: USD 1= NPR 102

Introduction

The 2015 Gorkha earthquake

An earthquake of magnitude M7.8 struck Gorkha district in Nepal on 25 April at 11:56 local time. The epicentre was at Barpak VDC (Village Development Committee) about 80 km NW of Kathmandu – 28.250°N latitude and 84.116°E longitude. The main shock was followed by many aftershocks, 421 of them with a magnitude ≥ M4 (up to 31 December 2015). Four aftershocks had a magnitude greater than M6.0, including one of magnitude, M7.3 on 12 May – 17 days after the first big earthquake – with epicentre in Sindhupalchok district. Many of the large aftershocks occurred to the east of the main shock. The earthquake occurred as a result of faulting confined to the subsurface approximately 14 km deep near the foothills of the Himalayan range. The fracture propagated about 150 km to the east and 60 km to the south of Barpak. The perceived shaking was considerable (Figure 1).

Figure 1: **USGS modelled shake intensity caused by the main shock (magnitude, M7.8) of the Gorkha earthquake on 25 April 2015**



Map Version 9 Processed 2015-07-02 22:51:16 UTC

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

Source: USGS, http://earthquake.usgs.gov/earthquakes/eventpage/us20002926#shakemap

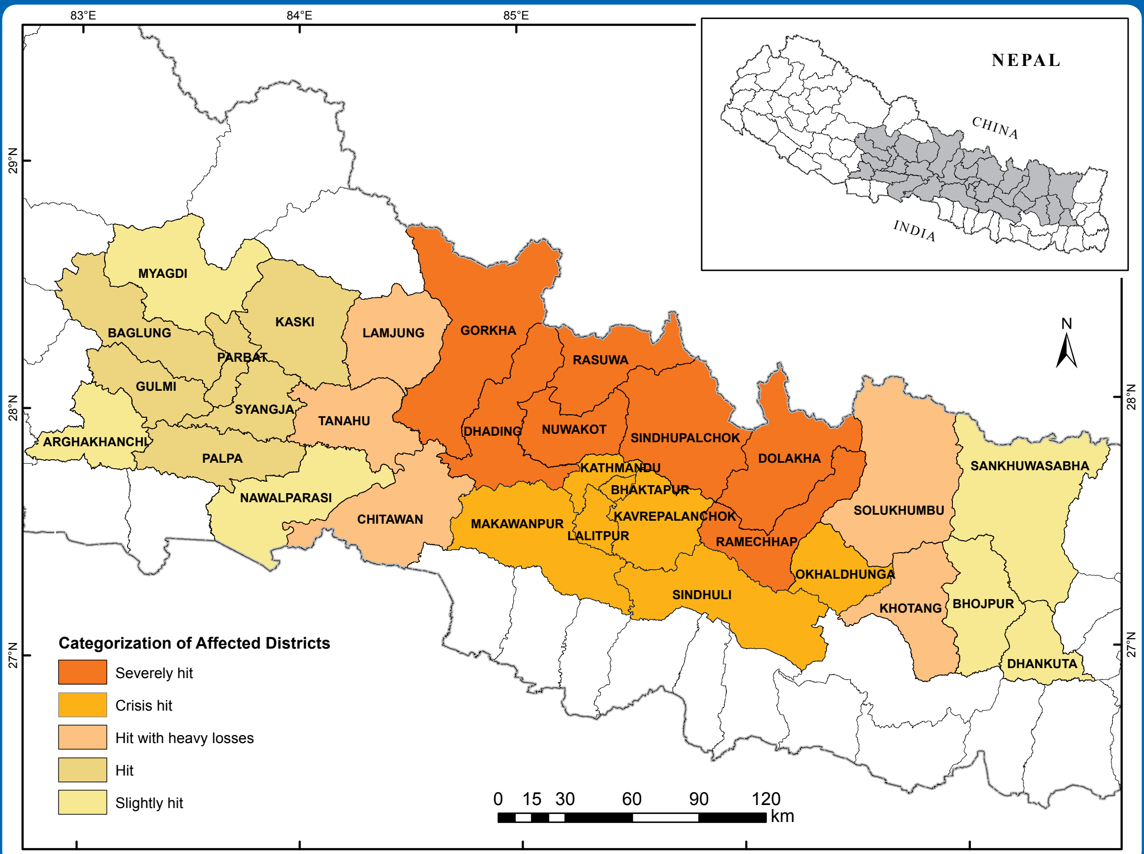
Effect on the population – human and economic loss

The total death toll close to the epicentre in Barpak VDC was 72, nearly 70% of them women and girls, and about 70% children (9 years and below) and the elderly (60 years and above). Almost all the houses in Barpak VDC were destroyed, 1,365 of 1,400. Among the districts affected, loss of life was highest in Sindhupalchok to the east with more than 3,438 people killed (GON).

It is estimated that the lives of eight million people, almost one-third of Nepal's population, were impacted by the earthquake and aftershocks (NPC 2015b). Within Nepal, there were more than 8,800 casualties, 22,000 people reported injured, and 100,000 people displaced. Additional deaths, injuries, and damage occurred in nearby areas of China (Tibet Autonomous Region), India, and Bangladesh, although Nepal bore the brunt of the impact. The estimated total economic value of the disaster (damage and losses) due to the earthquakes was USD 7 billion (NPR 706 billion). Almost all sectors – social (housing and human settlements, health, education, and cultural heritage), productive (agriculture, irrigation, commerce, industry, tourism, and finance), infrastructure (electricity, communications, community infrastructure, transport, and water and sanitation), and cross-cutting (governance, disaster risk reduction, and environment and forestry) were seriously affected. The National Planning Commission (NPC) Post Disaster Needs Assessment (PDNA) Report (NPC 2015a) identified 31 of the country's 75 districts as affected, of which seven were declared 'severely hit' (the worst category) and seven 'crisis-hit' (Figure 2).

The earthquakes pushed an additional 2.5 to 3.5% of the Nepalese population into poverty in 2015/16 – more than 700,000 people (NPC 2015b) According to NPC (2015b), 498,852 houses were completely damaged and 256,697 partially damaged. Many homes and public buildings sustained less immediately apparent structural damage, some of which may not yet have been recognized and/or recorded. Such properties will have increased vulnerability to any future earthquake activity.

Figure 2: **Categorization of districts affected by Gorkha earthquake 2015**



Source: After NPC 2015b

Earthquake-induced geohazards

Geohazards are events caused by geological/geomorphological features and processes that present severe threats to humans, property, and the natural and built environment. Typical examples include earthquakes, floods, landslides, volcanoes, avalanches, and tsunamis. In terms of number of fatalities, earthquakes and floods are often considered the most important. Geohazards can be relatively small features, but they can also attain huge dimensions and can have a marked local and regional socioeconomic impact. An earthquake is itself a geohazard, but can also cause secondary and tertiary geohazards (induced geohazards) through chains or cascades of hazardous processes, such as landslides and mass flows, landslide dams, and landslide dam outbursts.

As well as human lives, the disaster losses from the Gorkha earthquake and its aftershocks included both loss and damage of property and infrastructure directly induced by the shaking of the earthquake, and loss and damage from earthquake-induced geohazards. This report is concerned with these secondary, earthquake-induced, geohazards – mainly landslides, landslide dams, avalanches, and the potential for glacial lake outburst floods (GLOFs).

The earthquake activated or reactivated numerous landslides which caused major damage to settlements and infrastructure, and it was clear that these posed a continuing risk. An international volunteer group comprising scientists from the USA, Europe, and the region mapped the landslides using satellite images and paying special attention to those blocking rivers (Kargel et al. 2016; Sharma and Shrestha 2015; Collins and Jibson 2015), while a large group of Chinese scientists visited Nepal to study the geohazards, both from images and on the ground. The International Centre for Integrated Mountain Development (ICIMOD) worked together with both these groups and played an instrumental role in transferring important information to the government authorities of Nepal. ICIMOD prepared several reports related to the geohazards which were presented to the Ministry of Home Affairs, Government of Nepal (GON) and the Cabinet of Ministers and disseminated more widely through a dedicated geohazards page on ICIMOD's website. As a result of these and other activities, the GON formed a task force on geohazards and initiated a study on the impact of landslides on settlements. ICIMOD collaborated with several national institutions in providing technical and logistical support for the task force. The Skoll Global Threats Fund provided support to ICIMOD to study the status of earthquake-induced geohazards in the aftermath of the Gorkha earthquake and explore possible ways to reduce risk. This report describes the types of geohazards induced by the Gorkha earthquake and summarizes the results of the studies on their status and impact. The assessment is based on both primary and secondary sources of information.

The ICIMOD Study

The landslide map produced by the international volunteer team (Kargel et al. 2016) provided a rapid assessment in the form of a point map that was used to identify sites that required immediate investigation and action in the aftermath of the earthquake. However, additional and more detailed analysis including field information is required for assessment of the economic impact and long-term future needs. Supported by the Skoll Global Threats Fund, ICIMOD worked together with various organizations and groups to gather and collate detailed information on the occurrence and impact of the secondary geohazards induced by the Gorkha earthquake as follows.

The basic information on number and location of earthquake-induced landslides and the types of landslide processes was taken from the work done by the international volunteer group (Kargel et al. 2016). Information was then collected from the field at different levels – district, VDC, and community – and gathered directly from individual hazard events both on the ground and through aerial survey. Five types of study were carried out over a six-month period starting immediately after the earthquake and continuing to October 2015.

- In the first, a team from the Nepal Landslide Society identified those landslides impacting major infrastructure in 17 districts using satellite images (digitization from Google and DigitalGlobe images) and verification through fieldwork. The 17 districts included all those identified as severely hit, crisis hit, or hit with heavy losses by the Nepal Government (Figure 2) with the exception of the two districts of Makwanpur and Khotang where no landslides were identified.
- The second study focused on the socioeconomic impacts of landslides and debris flows. A team from the Geographic Information System and Integrated Development Centre (GISIDC) visited the district headquarters

and one community/landslide area in each of the seven severely affected districts (Dhading, Dolakha, Gorkha, Nuwakot, Ramechhap, Rasuwa, and Sindhupalchok) in order to assess the loss and damage and potential risk from landslides and debris flows. The team gathered data from official publications and directly from district and local offices, and carried out detailed observations of the selected landslides as case studies.

- The third study focused on landslide dams and the resultant dammed lakes and potential for outburst floods. Mapping of landslide dams was based on the work of the international volunteer group and ICIMOD.
- The fourth study focused on the impact of the earthquake on potentially dangerous glacial lakes. A team from ICIMOD and the University of Arizona carried out aerial observations of the lakes in Solukhumbu and Dolakha districts (with a brief ground visit to Tsho Rolpa), and also carried out aerial observations of landslides in these districts to further contribute to the other studies.
- The fifth study looked at the impact of earthquake-induced avalanches. ICIMOD, Utrecht University, and the international volunteer group worked together to investigate the mechanism and impact of the two disastrous avalanches associated with the earthquake.
- Finally, a team from ICIMOD carried out a series of observation visits in the severely affected districts of Gorkha, Nuwakot, Rasuwa, and Sindhupalchowk to provide additional verification and information complementing the above studies.

The results reported in the following are a synthesis of these studies.

Landslides

A landslide is the general name given to the movement of rock, debris, or earth down a slope along a surface of separation by falling, sliding, or flowing. Landslides include rock falls, deep failures of soil slopes, and shallow debris flows. They result from the failure of the materials which make up a hill slope and are driven by the force of gravity. They are an integral part of the mountain building process and are one of the chief means by which the uplifted mountain mass is transported down to lower valleys and basins.

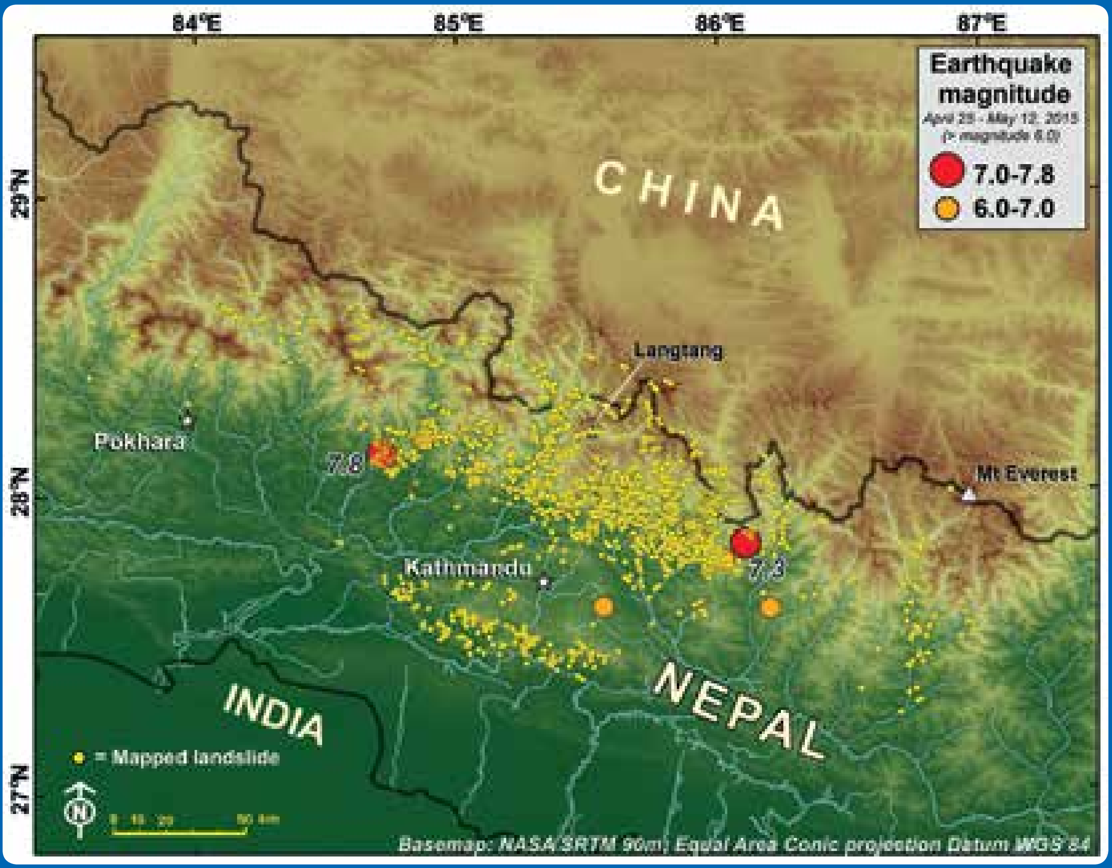
The Nepalese mountains occupy more than one-third of the Himalayan range, one of the fastest growing mountain ranges in the world. The area is generally prone to landslides, but the 25 April earthquake and its aftershocks triggered many new landslides, often in locations not previously affected. Remote sensing technology offered a very useful way of carrying out an immediate large scale rapid assessment directly after the earthquake. Satellite imagery was provided by NASA, DigitalGlobe, the Japan Aerospace Exploration Agency (JAXA), MacDonald Dettwiler and Associates (MDA), Planet Labs, Spot Image, the China National Space Administration, and the Indian Space Research Organisation and included imagery provided under the International Charter on Space and Major Disasters.

Distribution and characteristics

The earthquake-induced landslides were mapped by a volunteer group from the University of Arizona, ICIMOD, National Aeronautics and Space Administration and United States Geological Survey (NASA-USGS) Interagency Earthquake Response Team, British Geological Survey, Durham University, Chinese Academy of Sciences (CAS), Indian Space Research Organisation (ISRO), and others. The team involved in mapping (64 authors from different institutions listed in the main publication: Kargel et al. 2016) identified 4,312 landslides that were either directly triggered by the Gorkha earthquake and aftershocks, were conditioned by them and soon triggered by other causes, or had a high likelihood of having had such a relationship to the earthquakes (Figure 3 and Kargel et al. 2016). The number of landslides, while large, was much less than that induced by other earthquakes of similar magnitude. The location of the landslides is shown in Figure 3; 95% of them were in Nepal, with the remainder in adjoining areas of Tibet Autonomous Region (TAR), China. It was not always possible to make a definitive identification of these mass movements as due to the earthquake(s), but by tightly bracketing the 'before' and 'after' satellite imagery, it was possible to establish a very high likelihood that the earthquake(s) was the cause – either as the direct trigger or as a conditioning event that soon resulted in a landslide.

The mass movements induced by the Gorkha earthquake included several distinct types including most of those classified by Girty (2009). In general, landslides occur by gravitationally-driven movement of material with falling,

Figure 3: **Distribution of landslides (small yellow dots) induced by the Gorkha earthquake**



Source: Based on Kargel et al. 2016

toppling, sliding, spreading, or flowing. Rock debris (including soil and bedrock), ice and snow, and water can be involved in any ratio, and this ratio can change downslope as snow, water, or sediment is ingested. Over very large vertical drop distances, snow and ice can melt during descent due to the conversion of gravitational potential energy to heat; the amount of liquid water can increase downslope as a result of this effect or by ingestion of lake or stream water. Earthquake-triggered landslides are no different from other landslides in these regards; they differ only in the particular trigger mechanism. However, there is another important type of earthquake-triggered landslide consisting of a rotational slump failure of valley bottom sediments; these are important because they commonly enter into and sometimes block rivers, thus generating secondary landslide-dammed lake hazards.

The landslides identified by the international volunteer group were in the form of point maps. To generate polygon maps for impact assessment they were further digitized from Google and DigitalGlobe images and verified through fieldwork. The distribution of the digitized landslides is shown in Figure 4. A total of 5,159 landslides were mapped within the 17 districts (including landslides that existed prior to the earthquake). Earthquake-induced landslides were widespread in the earthquake-affected districts with a greater number in Dhading, Gorkha, Rasuwa, and Sindhupalchok (Figure 5). High resolution satellite data indicated that some landslides in Gorkha district were associated with avalanches.

The spatial distribution of earthquake-induced landslides depends on the factors that influence the dynamic response of the hillslopes undergoing seismic shaking (Jibson 2011; Newmark 1965) and is determined both by the conditions at the time of the triggering earthquake and the legacy of past events (Parker et al. 2015). In Nepal, the highest landslide densities overall (including pre-earthquake landslides) lay in the area between the epicentres of the three >M7.0 earthquakes of 26 August 1833, 25 April 2015, and 12 May 2015, highlighting the possible long-term effects of historic earthquakes (Kargel et al. 2016), while the highest density of earthquake-induced landslides lay in a broad swath between the two largest shocks.

Figure 4: **Landslide inventory of the study districts**

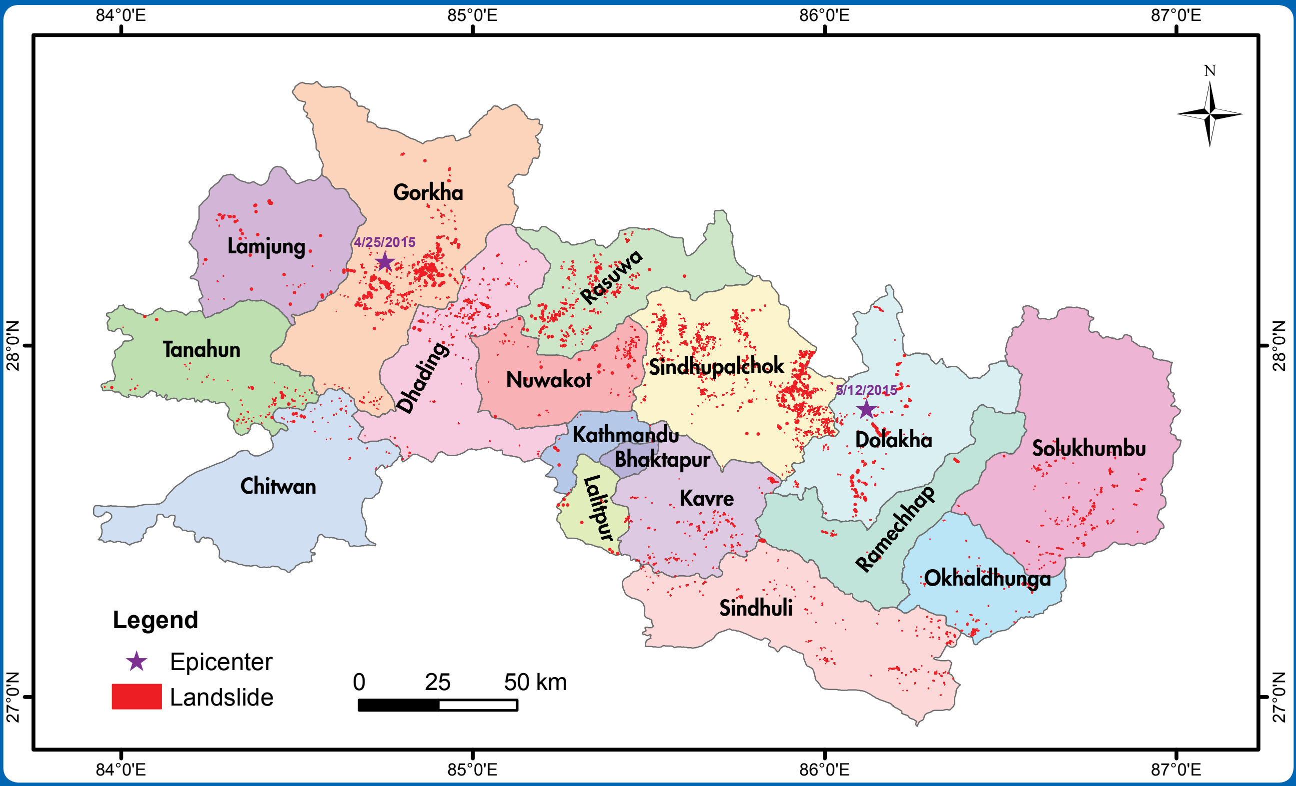


Figure 5: **Examples of landslides in Rasuwa (top) and Sindhupalchok (bottom) districts: to the left, field photos taken after the earthquake in July 2015; to the right, satellite images taken prior to the earthquake (top right 12 December 2014 and bottom right 27 August 2014**

Source: DigitalGlobe

Numerous landslides were identified that were either new or the reactivation of older landslides. The earthquake-induced landslides were mostly shallow (less than 5 m) failures, such as plane rockslides to wedge slides and rock falls, and debris falls and debris slides; deep seated failures were uncommon. Debris slides were the most frequent type, while rock falls were commonly triggered on steep slopes with numerous failures ranging from individual, small boulders to large falls (for example the rock fall at Tatopani village on the Nepal-Tibet border). Debris flows, valley fill collapse, and cut-and-fill failure types were also observed. The landslides mainly occurred on steep slopes, in areas of high shaking, near ridge crests, in the tectonically dropped blocks, in certain lithologies, and near lithological contacts or interbedding. The observations indicate that wave interactions with complex topography caused a general enhancement of shaking on or near ridge crests but had less impact on valley bottoms. The number and density of landslides appeared to be very sensitive to the amount of shaking; a slightly greater seismic disturbance might well generate a disproportionately larger number of landslides. Despite many concerns regarding the occurrence of earthquake-triggered landslide dams, only a few were identified.

Surprisingly the large (deep), old slides were not affected by the earthquake. For example, none of the landslides at Mulkharka and Ramche in Rasuwa district, the deep slides at Kothe and Daklan on the Arniko Highway, which are a few kilometres wide and more than 50 m long, or the soil slides on the Tama Koshi road were reactivated by the quake.

With the exception of the massive landslides in the Langtang valley, there were no giant landslides of the type which blocked the Hunza River at Atabad in Pakistan in 2010 creating a 22 km long lake. It has been suggested that the Atabad landslide itself might have been a five-year-delayed induced effect of the Kashmir earthquake of 2005 (Kargel et al. 2010).

The characteristics of the landslides induced by the Gorkha earthquake are illustrated in the following examples.

Multiple landslides were generated in the Dudh Koshi valley near Lukla on both sides of the river. Figure 6 shows several landslides, three of which were entirely new following the earthquake(s). The photo taken on 27 October 2015 shows several fresh landslides and a freshly reactivated old landslide (Figure 6a), in contrast to the CNES/Astrium image from 6 December 2014 (Figure 6b). Peak ground acceleration (PGA) at this point was about 0.08 g, i.e. relatively light shaking, nevertheless many landslides were triggered in the poorly lithified, poorly sorted clastic materials. The landslides were all 'thin-skinned', meaning that they didn't cut deep into the earth and were probably just a few metres deep. This was fortunate as several dwellings were located close to the head scarps of some of the landslides. The figure shows that the landslides affected two types of material: the relatively fine-grained rocks of what may be an old, degraded river terrace, and the bedrock of a nearby mountain ridge crest. Landslide deposits not related to the Gorkha earthquake are evident on the surface of the terrace, giving support to the interpretation of Götz et al. (2015) that the terraces in this area are the remains of former giant, river-damming Holocene landslides (Götz et al. 2015), or at least indicating a history of repeated aggrading, river-damming landslides. Either way, the prehistoric landslide event(s) were clearly enormous, pointing out the potential for future voluminous, deep-seated landslides. There are many houses within this old landslide area. The figure also shows a pronounced fracture in the mountains which did not fail (Figure 6e); had it done so, a massive, deep-seated landslide could have resulted, causing loss of the houses and damming the Dudh Koshi River.

A landslide complex was observed 3.5 km northwest of Bhadaure (Figure 7). The calculated PGA at this point was about 0.45 g (fairly strong shaking). A helicopter overflight on 28 October 2015 confirmed the fresh nature of much of the complex, but comparison of post-earthquake DigitalGlobe imagery with a pre-earthquake CNES/Astrium image (both rendered in Google Earth) showed that a large part of the complex had existed before the earthquake, but seismic reactivation had occurred. This example highlights the need for caution when interpreting what appear to be fresh landslides either in satellite imagery or airborne or ground-based imagery. The landslide complex included landslide elements that may have been caused by earthquake-driven ridgetop shattering (Collins and Jibson 2015), with prior conditioning by earlier landslides or simply weathering or other weaknesses in the rocks.

Socioeconomic impact of the landslides

The field survey focussed on the seven districts identified by the government as severely impacted: Dhading, Dolakha, Gorkha, Nuwakot, Ramechhap, Rasuwa, and Sindhupalchok (Figure 2). The area, household number, and population of the districts is shown in Table 1.

Figure 6: **Earthquake-triggered landslides in the Dudh Koshi valley near Lukla (west side of the river; location 27.666° N; 86.700° E)**

a) Oblique helicopter-borne photo acquired 27 Oct 2015. The scene width through the scene centre is about 700 m. The longest landslide is around 350 m long. b) The landslides did not exist twenty weeks prior to the earthquake, as seen in a Google Earth (CNES/Astrium) rendering of similar perspective from 6 Dec 2014. c) The three landslides that reached river level were all earthquake-related; one originated from terrace deposits, and the other two from the nose of a bedrock ridge crest composed of paragneiss. Another landslide can be seen in the distance (upper right). Peak ground acceleration (modelled) in this area was about 0.08 g, corresponding to weak shaking. (c) Enlargements from (a) showing the thin-skinned nature of these landslides. (d) A different helicopter-borne image shows an earthquake-induced landslide at the edge of Lukla (on the river's east bank) also visible in (a); this landslide also sources from terrace deposits – ancient deposits of a massive landslide which apparently blocked the river for a long time (Götz et al. 2015). (e) Enlargement of (a) shows the head scarp of one landslide, which receded by no more than a couple of metres relative to the pre-quake scene as shown in (f). This image pair also shows that the terrace source of the landslide is a boulder filled rockb fall similar to that documented by Götz et al. on the other side of Dudh Koshi. Other notable features in this area are deep, weathered bedrock fractures (arrows in panels a and b), which existed before the earthquake and fortunately were not discernibly reactivated. Such fractures indicate that a potential existed for much larger landslides than actually occurred.

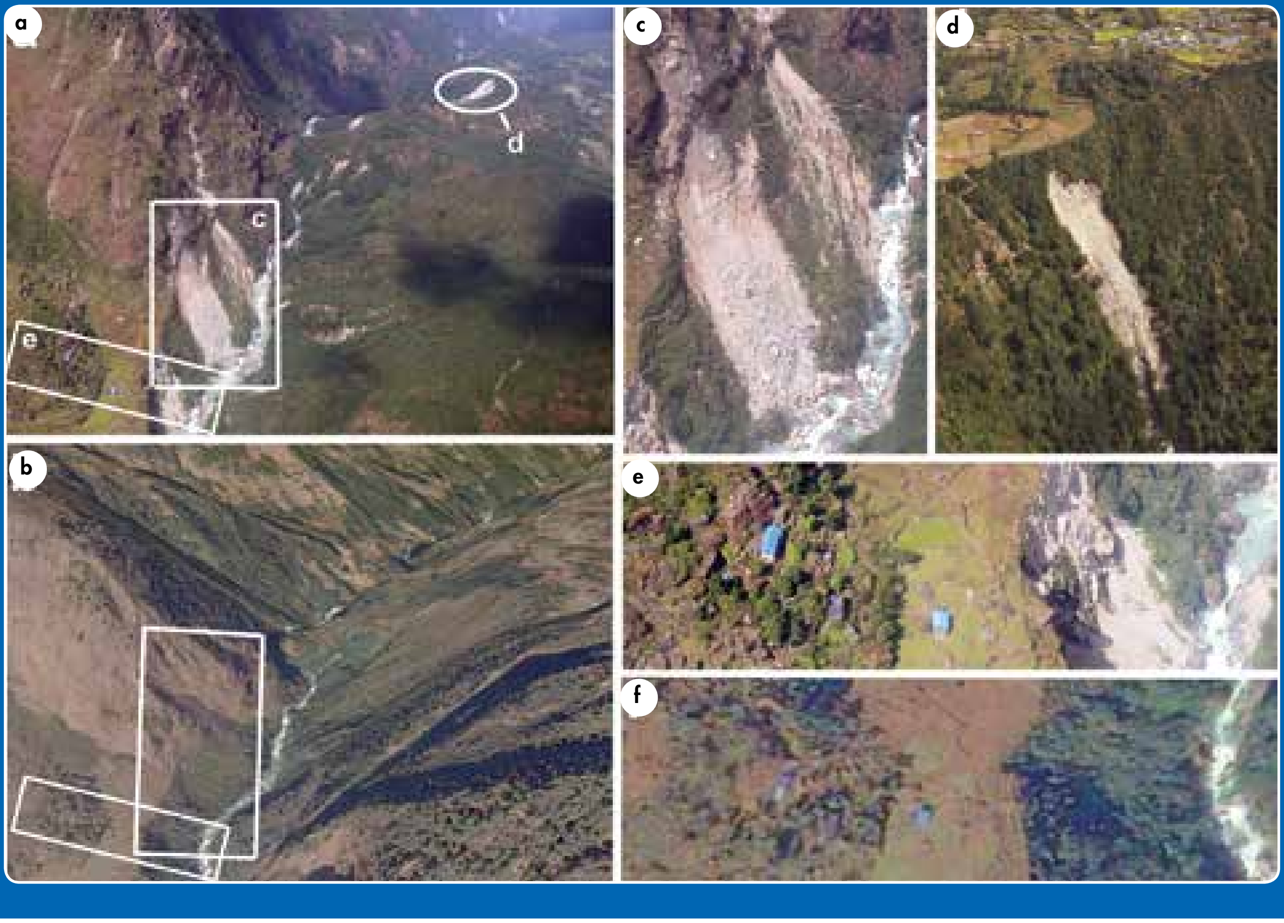


Table 1: **Area, household number, and population of the severely impacted districts**

District	Area (km²)	No. of VDCs	No. of households	Population	Population density (person/km²)
Dhading	1,926	50	73,851	336,067	174
Dolakha	2,191	52	45,688	186,557	85
Gorkha	3,610	67	66,506	271,061	75
Nuwakot	1,121	62	59,215	277,471	248
Ramechhap	1,546	55	43,910	202,646	131
Rasuwa	1,544	18	9,778	43,300	28
Sindhupalchok	2,542	79	66,688	287,798	113
Total	**14,480**	**383**	**365,636**	**1,604,900**	**111**

Source: NPC 2015b

The earthquake(s) had an impact on all sectors: social, productive, infrastructure, and cross-cutting (NPC 2015a, b). The destruction was widespread, covering residential and government buildings, heritage sites, schools and health posts, rural roads, bridges, water supply systems, agricultural land, trekking routes, and hydropower plants. Many rural areas in the central and western regions were devastated and further isolated due to damage and obstruction of roads and trails. Although much of the damage was the direct result of shaking, a considerable portion resulted from the impact of geohazards, especially landslides and debris flows. The majority of earthquake-induced landslides affected only forest land and/or small amounts of cultivated land but did not cause large loss of property, infrastructure, or life. However, a minority of landslides caused extensive damage, the most extreme of which were those in Langtang.

Data compiled by District Soil Conservation Offices on the number of households affected by geohazards was obtained for five of the seven severely impacted districts. (There was no data available for Nuwakot and Ramechhap.) The data showed that overall in these districts close to 9% of households were affected by geohazards in the form of landslides and debris flows (Table 2).

The nature of geohazards means that they are unevenly distributed. The proportion of VDCs affected within the different districts ranged from 51 to 72% with an average of 59%; and the percentage of households affected within individual affected VDCs ranged from less than 10% to more than 75% (Table 3, Figure 8).

Figure 7: **Landslide cluster northwest of Bhadaure (27.483° N; 85.950° E)**

This type of ridge top failure landslide was common following the Gorkha earthquake. The landslide cluster was visible on 12 December 2014 but was apparently reactivated by the seismic event. Note that the fresh landslide does not reach the valley at the bottom of the slope.

Table 2: **Number of households affected by landslides and debris flows induced by the Gorkha earthquake by district**

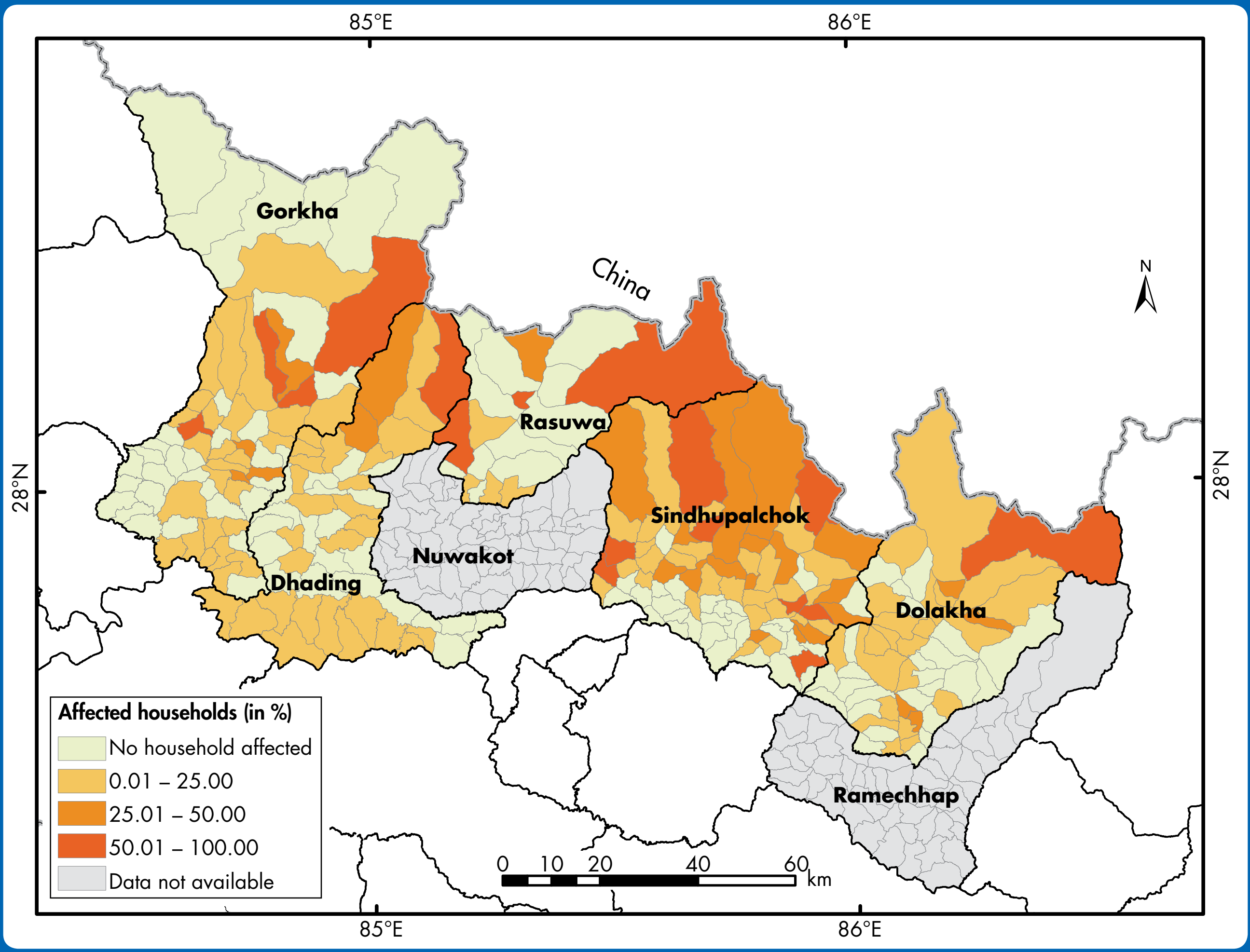
Districts	No. of households affected	Total no. of households in the VDCs affected by landslides	Percentage households affected at VDC level	No. of households in the district	Percentage of households affected at the district level
Dhading	2,982	42,469	7.0	73,851	4.0
Dolakha	3,427	25,189	13.6	45,688	7.5
Gorkha	4,340	37,183	11.7	66,506	6.5
Rasuwa	1,135	7,357	15.4	9,778	11.6
Sindhupalchok	11,991	42,804	28.0	66,688	18.0
Total	**23,875**	**155,002**	**15.1**	**262,511**	**9.1**

Table 3: **Number of VDCs and percentage of households affected by earthquake-induced landslides and debris flows**

	Number of affected VDCs						
	Total		Percentage of households affected				
District	No.	% of district	<10	10–24	25–49	50–75	>75
Dhading	29	58	19	7	2	1	0
Dolakha	27	52	4	18	4	1	0
Gorkha	34	51	18	8	4	2	2
Rasuwa	13	72	7	2	1	1	2
Sindhupalchok	53	67	13	16	16	4	4
Total	**156**		**61**	**51**	**27**	**9**	**8**

VDCs with more than 50% of households affected:
Dhading: Tipling
Dolakha: Gaurishankar
Gorkha: Kashigaon, Keraunja, Laprak, Lapu
Rasuwa: Langtang, Goljung, Dandagaon
Sindhupalchok: Bhotang, Dhuskun, Ramche, Tatopani, Attarpur, Gunsa, Mahankal, Thakani

Figure 8: **Percentage of households within individual VDCs affected by earthquake-induced landslides and debris flows**



One landslide or debris flow with a considerable level of loss and damage was selected in each district based on discussions at district headquarters, and was used as a case study for detailed assessment of loss and damage. The identified impacts were as follows:

- Golchina landside, Dhading: 3 deaths, 500 m of road, one water tank
- Mailung landslide, Dolakha: 2.5 ha (50 ropani) of cultivated land, 8 tonnes of standing crops, 300 m of trails, 300 m of irrigation canal
- Kulgaun landslide, Gorkha: 3 deaths, 0.3 ha (6 ropani) of cultivated land, 120 m of trails, 30 m of irrigation canal, and one chautari (resting platform)
- Jharlang landslide, Nuwakot: 1 death, 3.2 ha (62 ropani) of agricultural land, nearly 8 tonnes of paddy crop, 1 km of trails, 1 suspension bridge, 20 canals of different size
- Ghyapche landslide, Ramechhap: 4.6 ha (90 ropani) of cultivated land, 15 tonnes of standing crops (paddy, maize, millet), 5 km of trails, 4 irrigation canals, 500 m river embankment
- Ramche landslide, Rasuwa: 5 ha (100 ropani) of cultivated land, 2 km of trails, 1 km of road, 4 watermills
- Marming landslide, Sindhupalchok: 30 deaths, 10 houses, 1.6 ha (31 ropani) of cultivated land, 10 tonnes of standing crops, 500 m of road, 300 m of trails, 1 suspension bridge, 2 office buildings, 1.5 km of transmission line, 2 water mills, 4 parked vehicles

In addition, almost all the landslides had damaged forest land.

The estimated monetary value of the damage from the seven landslides is shown in Table 4. The value ranged from USD 2,451 from the Galchhina landslide in Dhading to USD 492,548 from the Marming landslide in Sindhupalchok, with an average of USD 125,490 per landslide. Close to half (48%) of the monetary value was from loss of land followed by infrastructure (42%), houses (8%), and crops (1%).

An attempt was made to estimate the share of earthquake-induced geohazards, especially landslides and debris flows, in the total per capita disaster loss district-wide in the seven most heavily affected districts from the earthquakes estimated by the National Planning Commission. The total estimated per capita loss from these geohazards in the seven severely affected districts ranged from USD 1,105 in Ramechhap to USD 2,508 in Dolakha, with an average of USD 1,884.

Table 5 shows the percentage of landslides within each district identified as impacting on, or posing an immediate risk to, different types of land use. More than 80% of the landslides posed a risk to forest land, while 24% threatened to constrict a river channel or form a landslide dam.

Table 4: **Monetary value of lost and damaged property and infrastructure from the seven selected earthquake-induced landslide**

Landslide, District	No. of deaths	Monetary value of loss and damage (USD)				Total
		House	Crops	Land	Infrastructure	
Galchhina, Dhading	3	0	0	0	2,451	2,451
Mailung, Dolakha	0	0	2,353	98,039	980	101,372
Kulgaun, Gorkha	3	0	0	1,765	1,176	2,941
Jharlang, Nuwakot	1	3,922	1,961	121,569	17,745	145,197
Ghyapche, Ramechap	0	0	5,196	35,294	27,941	68,431
Ramche, Rasuwa	0	0	0	49,020	16,569	65,589
Marming, Sindhupalchok	30	68,627	2,941	117,647	303,333	492,548
Total	**37**	**72,549**	**12,451**	**423,333**	**370,098**	**878,431**
Average	5	10,364	1,779	60,476	52,871	125,490
% of total		**8.3%**	**1.4%**	**48.2%**	**42.1%**	**100%**

Table 5: **Percentage of earthquake-induced landslides in each district threatening different sectors**

Sector[a]	Dhading	Dolakha	Gorkha	Nuwakot	Ramechhap	Rasuwa	Sindhupalchok	**Total**
Forest	84	60	92	99	54	99	89	**81**
Shrub	16	47	16	1	28	8	14	**19**
Cropland	4	10	11	13	16	5	14	**11**
Trails	5	11	8.	4	13	11	5	**8**
Roads	4	3	5	13	14	8	3	**6**
Settlements/ houses	0	1	0	3	1	3	3	**2**
Rivers	15	37	22	13	18	31	28	**24**

[a] Multiple impacts from one landslide possible

Future risks

Information on the elements that would be at risk from the seven case study landslides if they were to expand or reactivate was obtained in the field using focus group discussions. The elements can be summarized as follows:

- Golchina landside, Dhading: 44 people in 10 households with 10 houses, 20 livestock
- Mailung landslide, Dolakha: 9 people in 2 households with 2 houses
- Kulgaun landslide, Gorkha: 54 people in 9 households with 12 houses, main risk to 1.5 ha (30 ropani) cultivated land and crops
- Jharlang landslide, Nuwakot: 130 people in 30 households with 30 houses, 125 livestock; 500 m of road, 2 km of trail, 12 km of embankment, one school building, 2 km of transmission line, and one monastery
- Ghyapche landslide, Ramechhap: 175 people in 40 households with 40 houses, 185 livestock
- Ramche landslide, Rasuwa: 90 people in 15 households with 20 houses, 100 livestock, road
- Marming landslide, Sindhupalchok: 45 people in 10 households with 10 houses

In addition, large areas of forest with some rare species of wildlife would be exposed to future hazards from all these landslides.

The estimated monetary value of the property and infrastructure at risk is shown in Table 6. It ranged from USD 90,196 for the Galchhina landslide in Dhading to USD 1,009,115 for the Mailung landslide in Dolakha district, with an average of 396,078 per landslide. Infrastructure constitutes 42% of the total estimated value at risk, followed by land (38%), houses (15%), and livestock (5%).

Table 6: **Value of elements exposed to expansion or reactivation of the earthquake-induced landslides**

Landslide, District	People	Monetary value of property and infrastructure at risk (USD)				
		Houses	Livestock	Land	Infrastructure	Total
Galchhina, Dhading	44	44,117	2,941	24,509	18,627	90,196
Mailung, Dolakha	9	9,803	2,254	98,039	899,019	1,009,115
Kulgaun, Gorkha	54	117,647	10,588	14,705	1,960	144,900
Jharlang, Nuwakot	90	117,647	30,686	392,156	15,686	556,175
Ghyapche, Ramechhap	175	2,745	54,411	254,901	116,666	428,723
Ramche, Rasuwa	180	58,823	39,215	264,705	12,745	375,488
Marming, Sindhupalchok	45	68,627	980	0	98,529	168,136
Total	**597**	**419,411**	**141,075**	**1,049,015**	**1,163,232**	**2,772,743**
Average	85	59,916	20,154	149,859	166,176	396,106
Per cent		**15.1**	**5.1**	**37.8**	**42.0**	**100**

Assessment of affected infrastructure

Mapping of earthquake-induced landslide impacts was carried out for all the districts classed as severely hit, crisis hit, or hit by heavy losses by GON (Figure 2) (with the exception of Khotang and Makwanpur where there were no landslides). Of the total 5,159 landslides mapped in the 17 districts, 464 landslides in 11 districts affected roads, hydropower projects, bridges, irrigation systems, and/or buildings (houses, schools, and others) (Figure 9). The number of these landslides in each of the 11 affected districts is shown in Table 7; there were no landslides affecting infrastructure in the remaining six districts. Details of the affected infrastructure are provided in the following sections.

Table 7: **Number of landslides affecting infrastructure**

District	No. of landslides
Chitwan	5
Dhading	8
Dolakha	54
Gorkha	200
Kathmandu	5
Lalitpur	8
Lamjung	33
Nuwakot	14
Rasuwa	35
Sindhupalchok	90
Tanahun	12
Total	**464**

Settlements

A huge number of low strength masonry buildings were damaged by the earthquake. Of these, the number damaged by earthquake-induced landslides was relatively small, although still significant. The inventory of damaged buildings was digitized and the positions overlaid with the area of earthquake-induced landslides. A total of 109 buildings fell within landslide areas (Figure 10; Table 8). Not all damaged buildings were identified at the time of the inventory thus the actual number could be slightly higher

Figure 9: **Earthquake-induced landslides that affected infrastructure in the study districts**

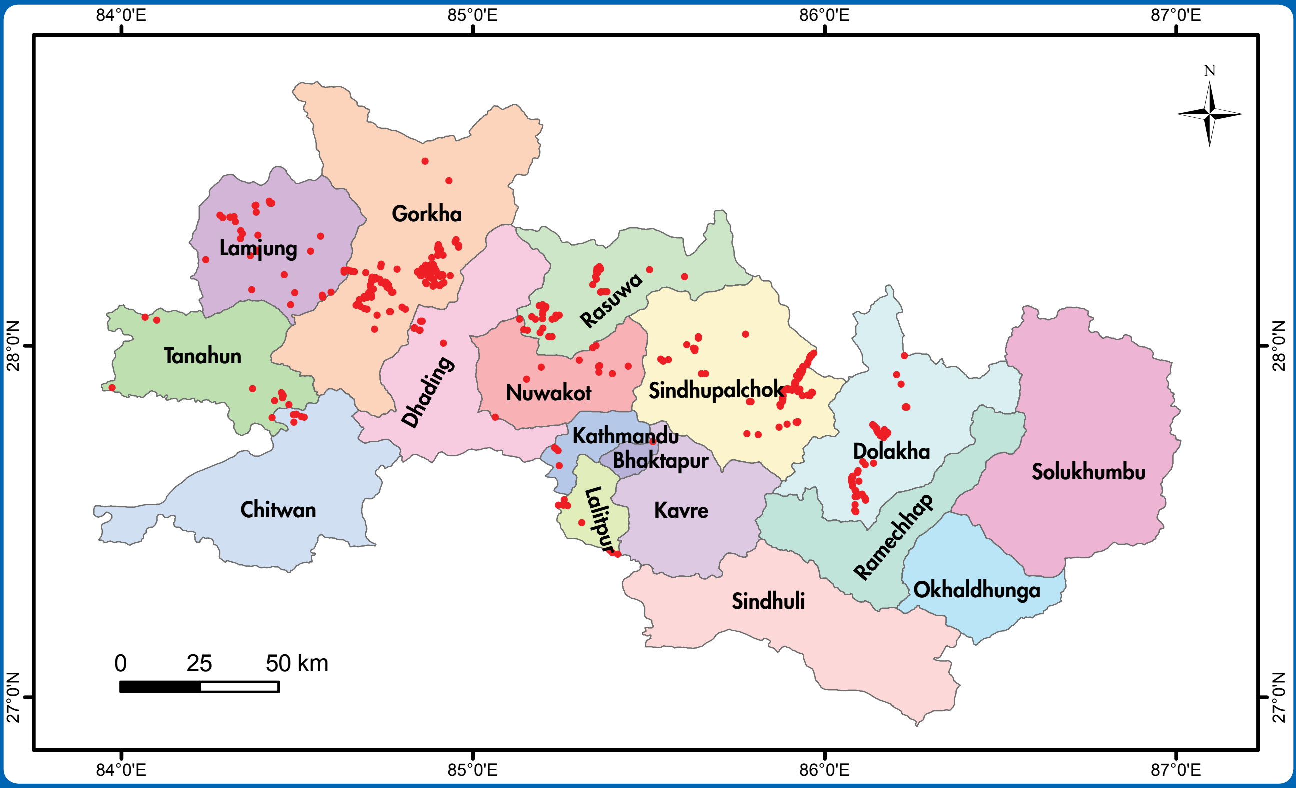
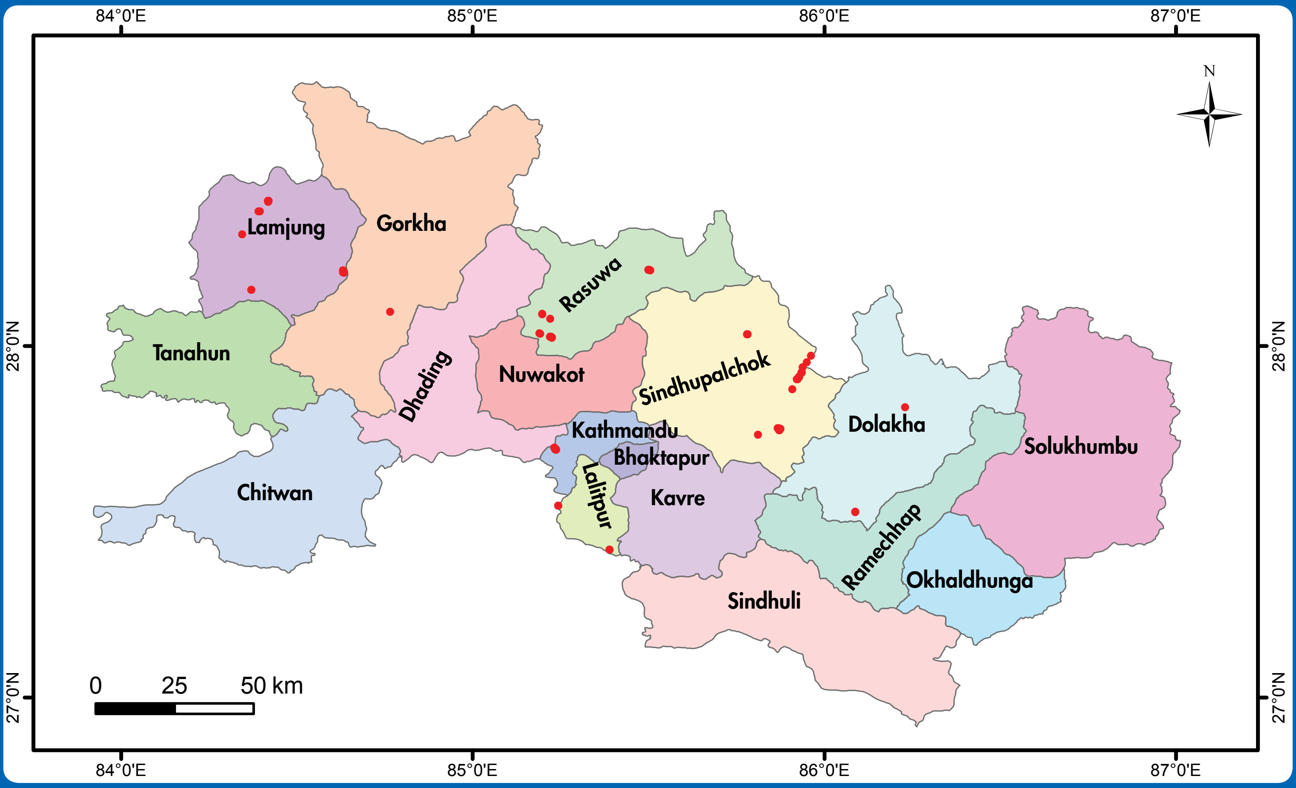


Figure 10: **Buildings damaged or destroyed by earthquake-induced landslides in the districts studied**



Field visits showed major destruction of newly-developed settlements by landslides along the Pasang Lamu Highway in the Trishuli valley (Rasuwa) and Kodari Highway along the Bhotekoshi/Sunkoshi valley (Sindhupalchok) (Figure 11), whereas older settlements were less affected by geohazards. Settlements in Tatopani village (at the Nepal-China border) were also hit by rock fall from the nearby mountain.

In Langtang valley (Rasuwa), an earthquake-induced rock fall triggered a debris flow and avalanche with an air blast resulting in devastating damage and killing more than 300 people (Kargel et al. 2016). Langtang and Gumba villages were completely destroyed – probably more than 100 houses overall. Structures that weren't directly buried in Langtang village and the surrounding areas were completely levelled by the landslide-induced air blasts. The sole exception was a partly damaged but still standing hotel protected underneath a cliff overhang.

Table 8: **Number of houses damaged or destroyed by earthquake-induced landslides in the districts studied**

District	No. of houses
Dolakha	3
Gorkha	1
Kathmandu	14
Lalitpur	4
Lamjung	23
Rasuwa[a]	26
Sindhupalchok	39

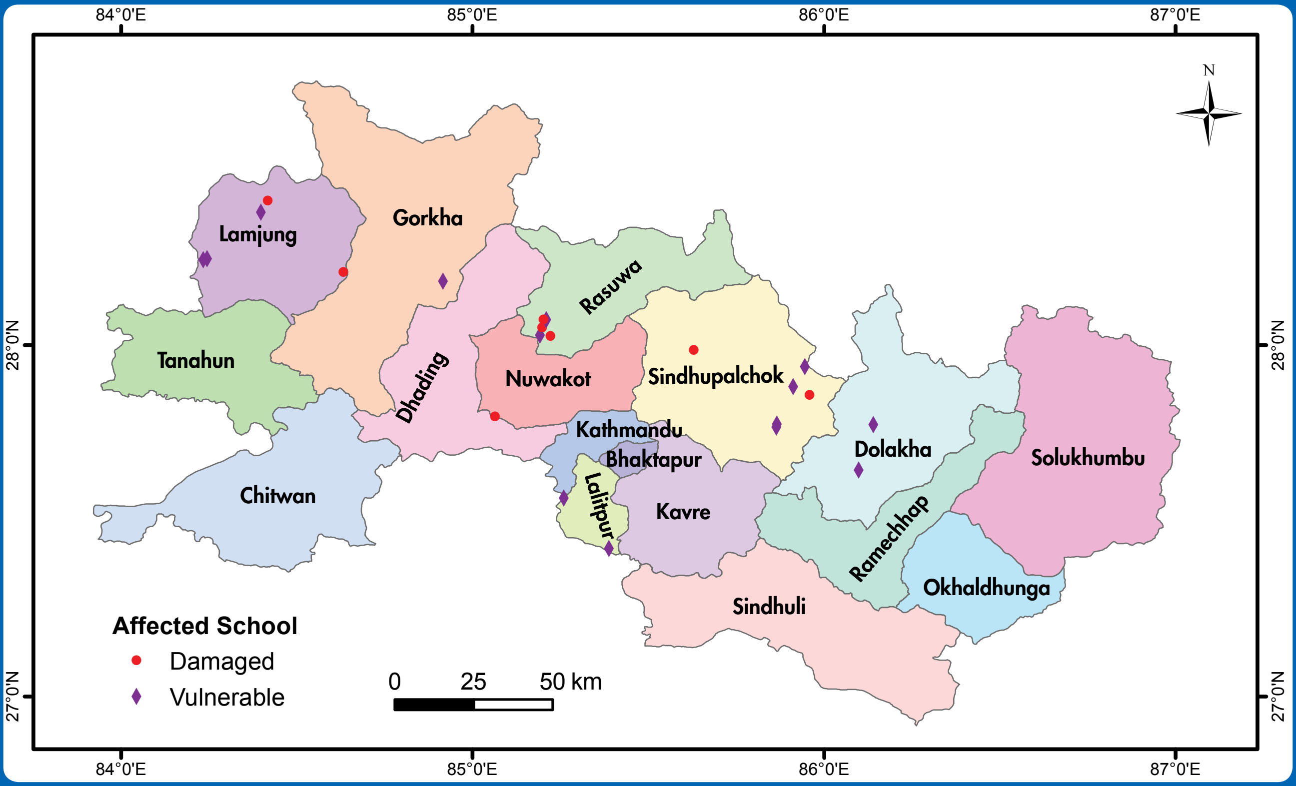
[a] Not including the ~100 houses destroyed in the Langtang valley

School buildings

Many school buildings in the study districts were severely damaged but only a few were damaged by landslides. The mapping identified a total of 22 school buildings damaged by earthquake-induced landslides (Figure 12; Table 9); eight directly hit and 12 schools made vulnerable.

Figure 11: **New settlements along the Kodari Highway were severely damaged by earthquake-induced landslides**

Figure 12: **Schools affected by earthquake-induced landslides in the districts studied**



Hydropower projects

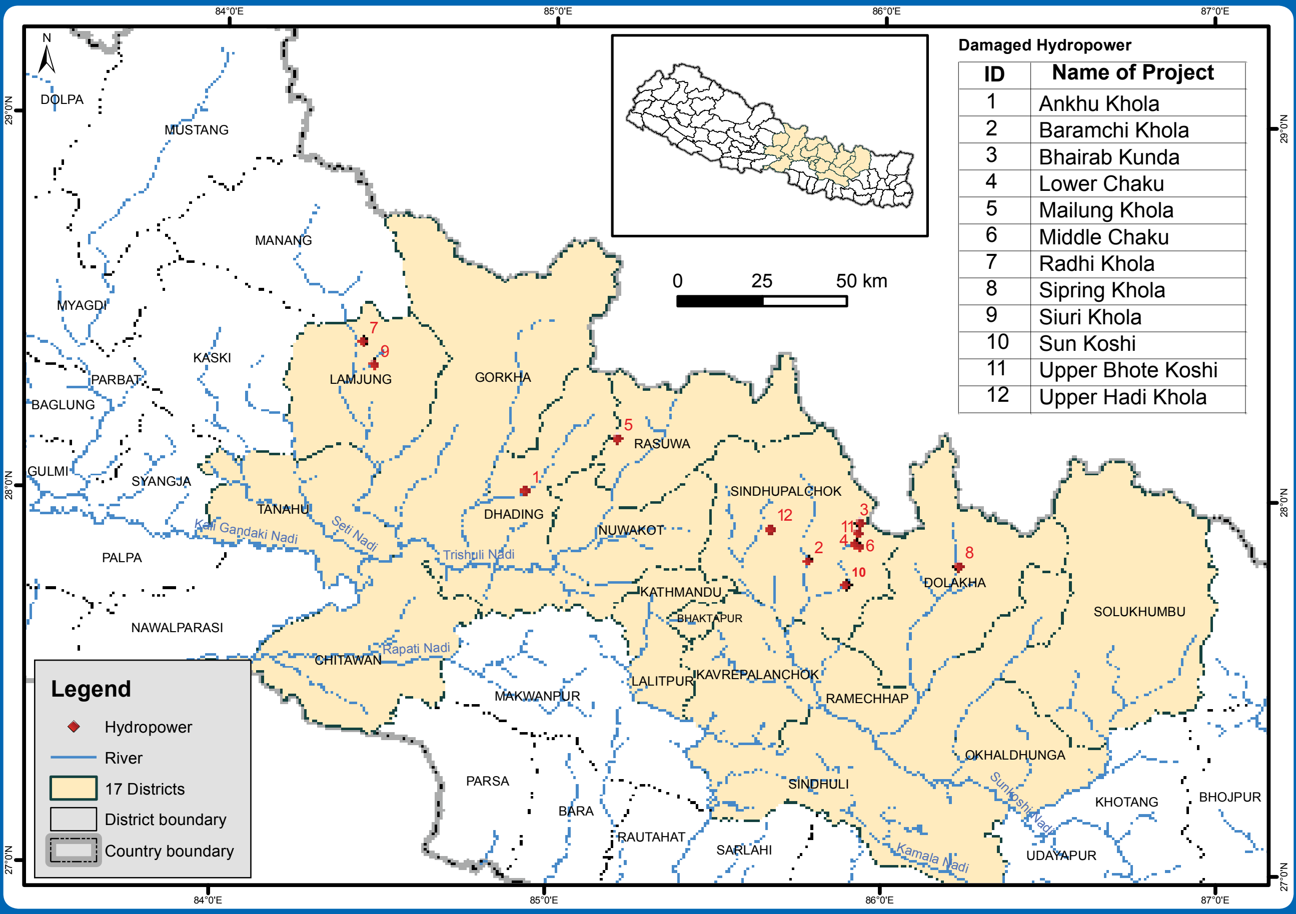
Nepal's energy sector sustained losses valued at USD 184 million as a result of the earthquake and continuing aftershocks. The draft Post Disaster Needs Assessment (NPC 2015a,b) prepared by the Ministry of Energy put the total cost of the physical damage to the public sector as approximately USD 70 million, and to the private sector USD 113 million. Hydropower facilities with a combined capacity of 115 MW out of the total installed capacity of 787 MW in the country (on-grid as well as off-grid) were severely damaged, and facilities with a combined capacity of 60 MW were partially damaged. The Independent Power Producers' Association Nepal (IPPAN) identified 21 operational hydropower plants that had been impacted by the earthquake affecting 109 MW of energy production.

Table 9: **School buildings damaged and vulnerable due to earthquake-induced landslides**

District	No. of affected schools	Damaged	Vulnerable
Dolakha	2	NA	2
Gorkha	1	NA	1
Lalitpur	2	NA	2
Lamjung	5	2	3
Nuwakot	1	1	NA
Rasuwa	5	3	2
Sindhupalchok	6	2	4

Much of the damage resulted from the direct impact of shaking, but a number of installations were damaged by rock falls and landslides. The location of the hydropower projects affected by earthquake-induced landslides is shown in Figure 13 and the damage suffered is summarized in Table 10. Landslides and rock falls also affected a number of projects under construction. The Upper Tamakoshi Hydroelectric Project in Sindhupalchok, the largest hydroelectric project under construction (456 MW, run-of-the-river) has experienced considerable delays in completion due to damage caused by the landslides, mainly to the access road. The 111 MW Rasuwagadhi hydropower station sustained serious damage due to a landslide and debris flow, and the 24 MW Upper Trishuli 3A project was hit by landslides and much of the access road to the dam was washed away.

Figure 13: **Location of hydropower projects affected by earthquake-induced landslides and rock fall**



Damaged Hydropower

ID	Name of Project
1	Ankhu Khola
2	Baramchi Khola
3	Bhairab Kunda
4	Lower Chaku
5	Mailung Khola
6	Middle Chaku
7	Radhi Khola
8	Sipring Khola
9	Siuri Khola
10	Sun Koshi
11	Upper Bhote Koshi
12	Upper Hadi Khola

Table 10: **Hydropower projects affected by earthquake-induced geohazards (including landslides, rock falls and debris flows)**

Project	District	Capacity (kW)	Impact
Ankhu Khola	Dhading	8,400	Substation, powerhouse, and 11 poles destroyed or damaged by landslide
Baramchi Khola	Sindhupalchok	4,200	Penstock pipe burst due to rock fall, no access to power plant
Bhairab Kunda	Sindhupalchok	3,000	Tunnel leakage, penstock burst, switchyard damage, transmission line damage, due to rock fall
Upper Bhote Koshi	Sindhupalchok	45,000	Penstock burst due to rock fall, powerhouse submerged due to penstock burst, rock fall continued after earthquake, no access to power plant
Lower Chaku	Sindhupalchok	1,765	No access to power plant due to landslide
Sun Koshi	Sindhupalchok	2,500	Landslide at penstock alignment and landslide at headworks area, no access to power plant
Middle Chaku	Sindhupalchok	1,800	No access to power plant due to landslide
Radhi Khola	Lamjung	4,400	Headrace pipe deformed by rock fall; bearing of one generator found broken; cracks in three penstock anchor blocks, foundation settlement
Sanima	Sindhupalchok	2,500	Landslide, no details
Sipring Khola	Dolkha	9,658	Landslide at penstock alignment
Upper Chaku	Sindhupalchok	22,200	Landslide, no details
Upper Hadi Khola	Sindhupalchok	991	Rock fall with large boulders on switchyard damaged walls of the powerhouse and staff quarters; steel pipe of head-race cracked in several places
Mailung Khola	Rasuwa	5,000	Significant damage to headworks, desander, penstock pipe, and powerhouse due to landslide
Siuri Khola	Lamjung	4,950	Headrace pipe damaged/deformed in numerous places due to rock fall, small cracks in anchor blocks and saddle, foundation settlement

(IPPAN 2015 and others)

Figure 14 shows some of the damage suffered by existing projects and projects under construction.

Transportation

The transportation sector was severely affected by the earthquake, mainly as a result of earthquake-induced landslides. The PDNA report (NPC 2015a,b) estimated a total loss of USD 216 million (USD 169 million damage and USD 48 million losses) in the transport sector.

The locations of damaged road sections were obtained from the Ministry of Home Affairs (MOHA) database (DRR Portal Nepal 2015) and the sections damaged by earthquake-induced landslides mapped (and updated) through a Google Earth image search. Some affected roads were further investigated during the field visits. The length of roads affected by earthquake-induced landslides in the districts studied is summarized in Table 11. More than 456 km of road was affected by the earthquake, with more than 33 km of road damaged by earthquake-induced landslides. Affected stretches were identified in 10 of the 17 districts studied. Among others, 11.3 km of the Arniko Highway, a 2.5 km section of the Lamosanghu-Charikot-Lamabagar road, and a 3.6 km section of the Chanaute-Barpak road were damaged.

Figure 14: **Hydropower plants damaged by landslides**

a) Penstock of the Bhotekoshi; b) Upper Trishuli (under construction); and c) Rashuwagadi (under construction)

Table 11: **Roads affected by earthquake-induced landslides (modified from DRR Portal Nepal 2015)**

District	Affected road length (km)	Damaged due to landslide (m)	Embankment settlement (m)	Pavement damage (m)	Retaining structure damage (m)	Drainage damage (m)
Dolakha	101	3,150	4,800	4,700	2,350	4,300
Gorkha	60	8,925	5,500	NA	580	NA
Lalitpur	24	350	NA	NA	NA	NA
Nuwakot	95	675	NA	2,950	1,000	NA
Rasuwa	71	610		2,250	1210	NA
Sindhuli	NA	300	300	1000	NA	NA
Sindhupalchok	105	18,950	24,000	22,600	22,200	23,650
Total	**456**	**32,960**				

Bridges

Most of the bridges along the national highways survived the earthquake itself, but a few bridges were damaged or destroyed by rock falls derived from earthquake-induced landslides in the surrounding catchments. These included the bridge at Tamakoshi in Gongar, the Friendship Bridge at the Nepal-China border (Tatopani), Phulping bridge near Lharcha, and Rasuwa Gadi bridge at the Rasuwa Gadi border (Figure 15). Other bridges along minor access roads may also have been affected but as yet there is no documentation available.

Figure 15: **Bridges damaged by rock fall following earthquake-induced landslides**

a) Rasuwa Gadi bridge damaged by rock fall; b) Friendship Bridge damaged by rock fall, showing Bailey bridge built by the Chinese Government for vehicles to cross; c) Phulping Bridge on the Kodari highway damaged by rock fall; d) severe damage from a rock fall to the bridge under construction to access the new dry port along the Kodari highway

Irrigation System

The PDNA report (NPC 2015a,b) identifies a total of 290 irrigation schemes in 31 districts with earthquake-related damage, mostly as a result of landslides and debris flow, with estimated losses of USD 3.8 million. Two hundred irrigation schemes were damaged in the districts studied (111 in Gorkha, 26 in Dhading, 13 in Nuwakot, 5 in Rasuwa, 7 in Sindhupalchok, 38 in Dolakha).

Landslide-Dammed Rivers

Landslide dams, followed by flooding behind the dam and outburst floods when the dam fails, generate one of the most common forms of natural disaster in steep and narrow mountain valleys (Schuster and Costa 1986; Costa and Schuster 1988, 1991; Evans et al. 2011). The two major causes of landslides leading to dam formation are precipitation and earthquakes: approximately 50% of dam-forming landslides result from rainstorms and snowmelts, 40% from earthquakes, and 10% from other factors (Schuster 1993; Peng and Zhang 2012). The factors responsible for the development of landslide dams include the geometry of the valley in relation to the geometry and volume of debris, and the discharge of the river. Schuster et al. (1998) described four groups of factors responsible for the spatial distribution of landslide dams:1) seismic intensity, 2) slope gradient and topography, 3) lithology/ structure and weathering properties, and 4) soil moisture and groundwater content.

Landslide dams can be generated by various types of mass movements ranging from rock falls and rockslides in steep walled, narrow canyons to earth slumps in flat river lowlands (Costa and Schuster 1988; Schuster 1995). Schuster (1995) found that about 40% of landslide dams were formed by rock and soil slumps and slides; 30% by debris, earth, and mud flows; 25% by rock and debris avalanches; and less than 10% by sensitive clay failures, rock falls, and earth falls.

Following the Gorkha earthquake, people at many international research centres and organizations scanned satellite images to identify landslides and landslide dams in the earthquake affected area. On 1 May 2015, the Pacific Disaster Center (PDC) identified landslide dammed rivers in the Lamjung, Langtang, Manang, and Myagdi valleys. The Chinese Academy of Sciences (CAS) quickly organized an expert team to aid the Nepal Government in disaster assessment and relief. The team focused on geohazard investigation using Chinese satellite (GF- 1) images and other satellite data. The CAS team identified ten additional landslides across rivers in Gorkha, Rasuwa (including Langtang), and Sindhupalchok, with the most serious situation in Rasuwa. There were many landslides along the Trishuli River valley on both sides of the river from Dandagaum to the border. Some of the landslide dammed rivers had formed new lakes which threatened the safety of villages and roads downstream. The international volunteer group was instrumental in identifying the earthquake-induced landslide dams and thus facilitating investigative and ameliorative action. The following sections give some examples of these post-earthquake landslide dams. The location of the landslide dams are given in Figure 16.

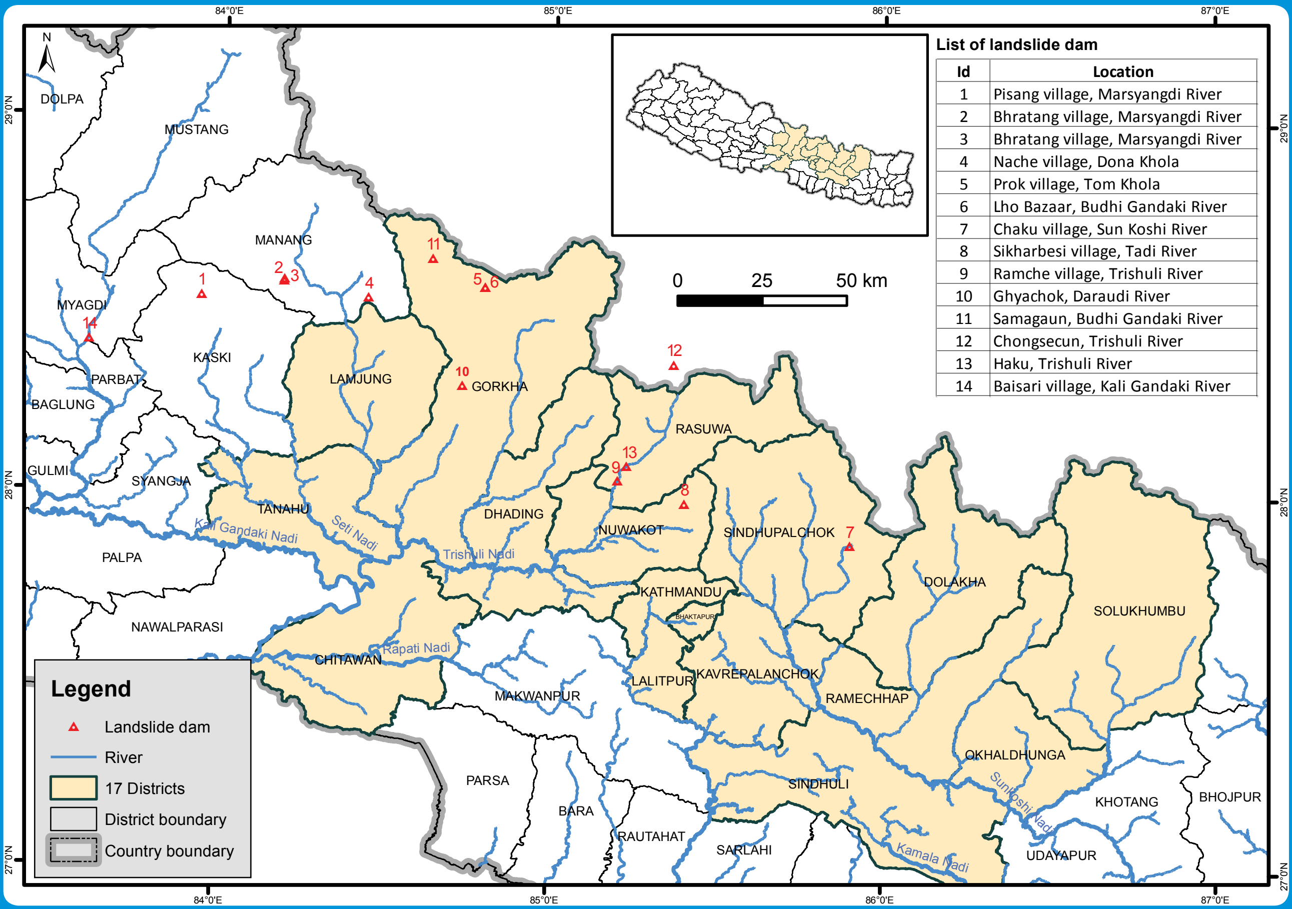
Details of selected landslide dams

Marsyangdi River near Lower Pisang

A landslide blocked the Marsyangdi River near lower Pisang village at 28.526°N, 83.936°E. A small landslide partially across the river was identified in an image from 27 April (and not visible on 21 April), and a further large landslide 400 m downstream of the first in an image from the 2 May. The second landslide blocked the river forming a lake 38 m wide and 500 m long (Figure 17). The river drained through the debris and there was no serious damage or casualties, but Lower Pisang village was still thought to be at risk and to need monitoring.

A further landslide blocked the Marsyangdi River close to Bhratang village in Manang at 28.567°N, 84.183°E (Figure 18). The blockage was identified in an image from 27 April which showed 10 houses on the left bank at the

Figure 16: **Location of stretches of road damaged by earthquake-induced landslides**



List of landslide dam

Id	Location
1	Pisang village, Marsyangdi River
2	Bhratang village, Marsyangdi River
3	Bhratang village, Marsyangdi River
4	Nache village, Dona Khola
5	Prok village, Tom Khola
6	Lho Bazaar, Budhi Gandaki River
7	Chaku village, Sun Koshi River
8	Sikharbesi village, Tadi River
9	Ramche village, Trishuli River
10	Ghyachok, Daraudi River
11	Samagaun, Budhi Gandaki River
12	Chongsecun, Trishuli River
13	Haku, Trishuli River
14	Baisari village, Kali Gandaki River

Figure 17: **Marsyangdi River near Bhratang (left picture courtesy Mukhiya Gotame, Manang villager; right, WorldView-2 satellite image 2 May 2015)**

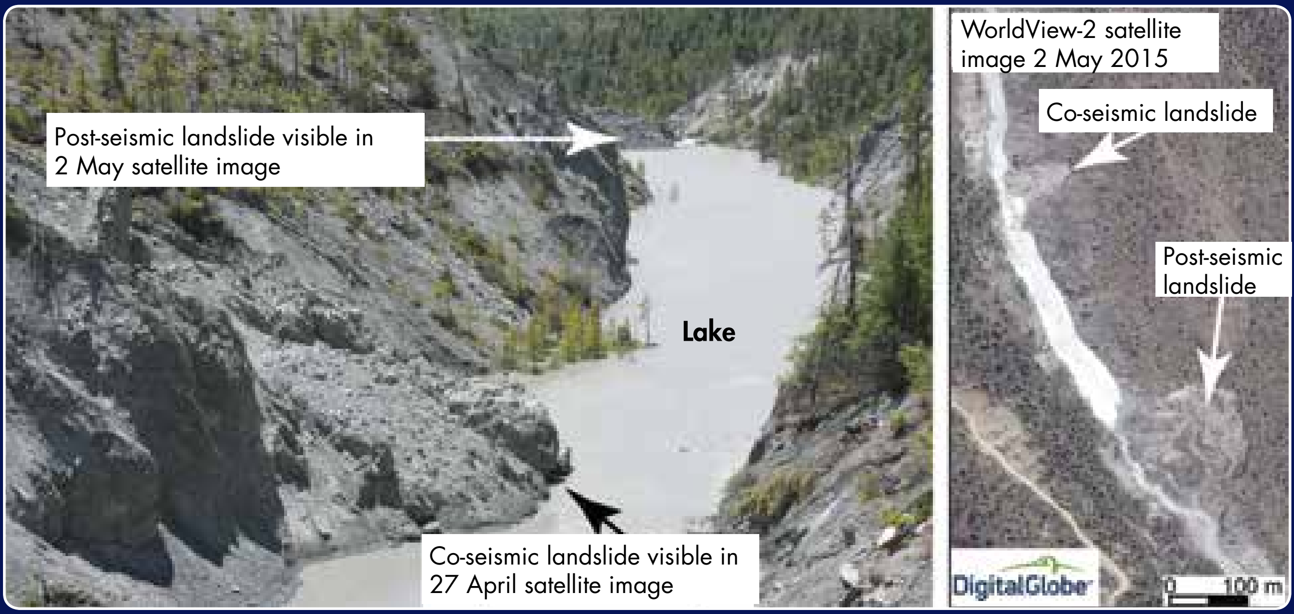


Figure 18: **Landslide blocking the Marsyangdi River close to Bhratang village in Manang**

Source: WorldView 1 image 29 April 2015

risk of being washed away. The WorldView 1 image of 29 April showed the river discharging through a natural tunnel under the landslide debris, saving the houses. It is likely that this mass movement was primarily a snow avalanche.

Dona Khola downstream of Thulagi lake

A landslide blocked the Dona Khola, a tributary of the Marsyangdi River, downstream of Thulagi lake and about 7 km upstream of Nache village at 28.526°N, 84.441°E. Four debris flows were seen along the tributaries of the Dona Khola, one of which had crossed the river, in the WorldView 02 image from 2 May 2015 (Figure 19). There was no indication of actual blockage or development of a dammed lake.

Tom Khola tributary of Budhi Gandaki near Prok village

A landslide blocked the Tom Khola, a tributary of the Budhi Gandaki, upstream of the villages of Ghapsya and Ghap and near Prok village in Gorkha, at 28.559°N, 84.793°E (2,500 masl). A large volume of water was stored in the lake formed behind the landslide which continued to grow (Figure 20). By 3 May, the river had cut through the landslide dam and was flowing, although not necessarily at full capacity. The river was considered to require continued monitoring, an aerial survey, and detailed risk assessment and monitoring downstream.

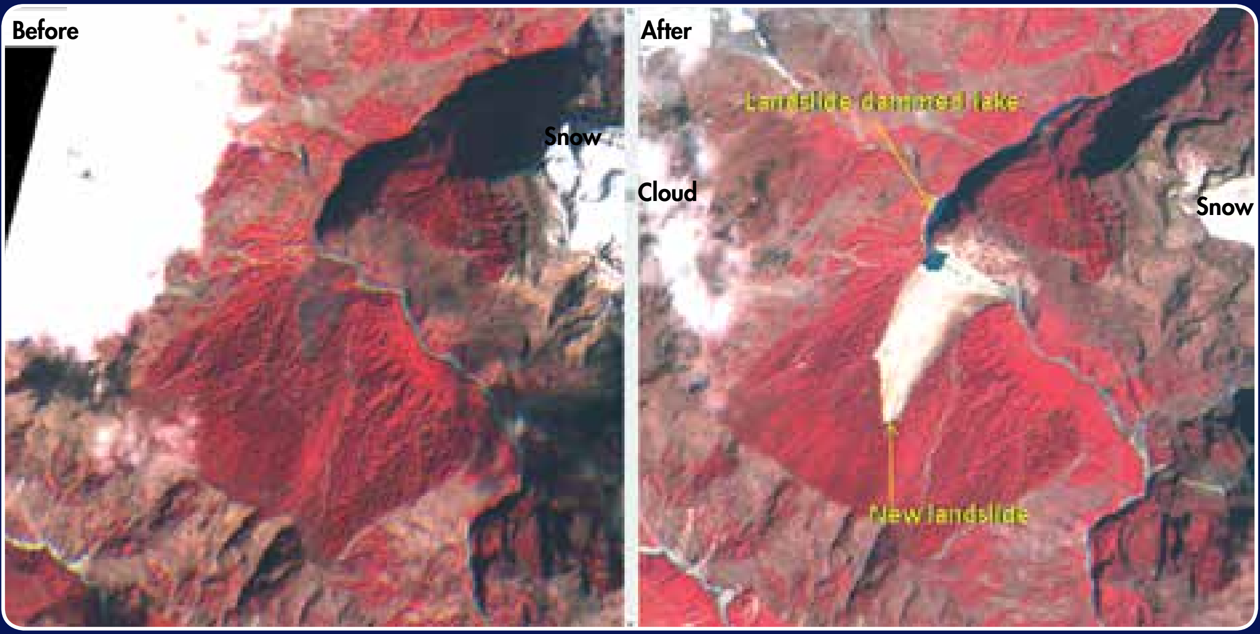
Budhi Gandaki, Lho Bazaar

A landslide blocked the Budhi Gandaki upstream of Lho Bazaar in Manasulu at 28.559°N, 84.793°E (2,500 masl) (Figure 21). The landslide was a debris flow from the Lanjam glacier terminal moraine; it narrowly missed the Lho and Lhi villages. Water accumulated behind the dam and then started flowing beneath the debris.

Figure 19: **Debris flows from tributaries across the Dona Khola**

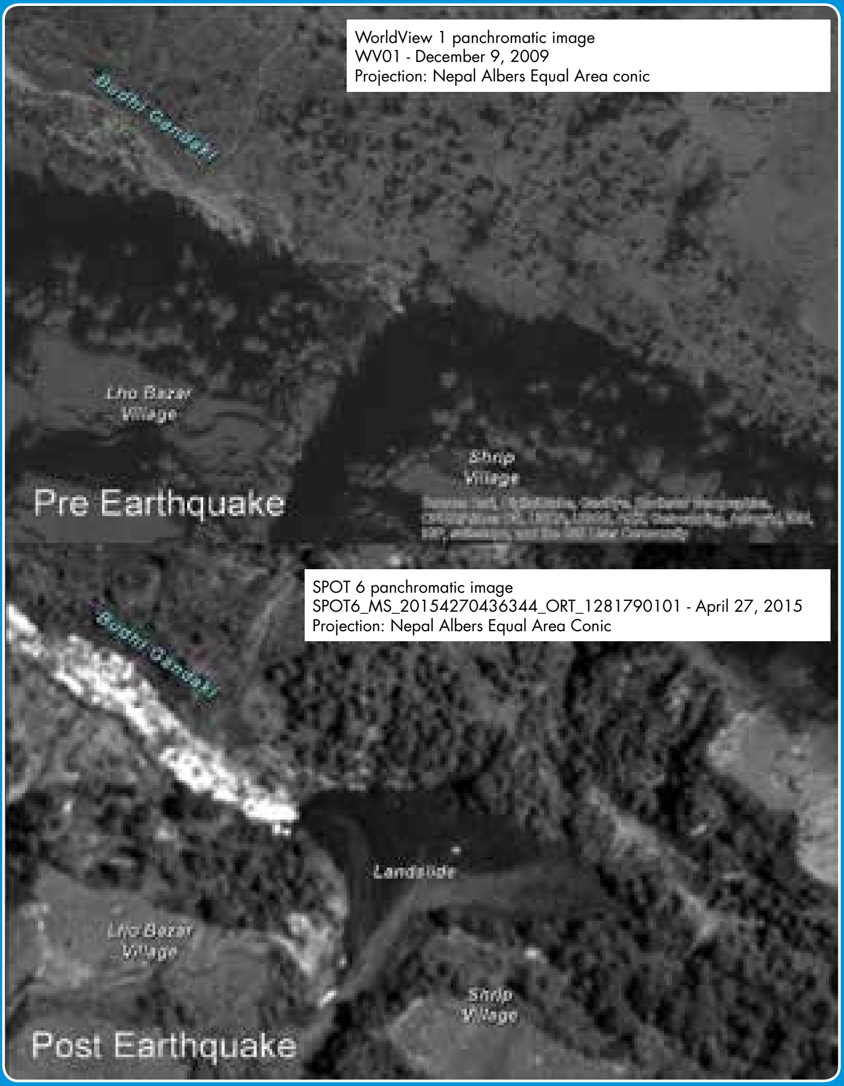
Source: WorldView 02 image, 2 May 2015

Figure 20: **Landslide blocking the Tom Khola near Prok village, Gorkha**



Source: Resourcesat-2 LISS IV Mx, ISRO; left, 1 April 2015, right, 30 April 2015

Figure 21: **Landslide from Lanjam glacier terminal moraines blocking the Budhi Gandaki River in Manaslu**



WorldView 1 panchromatic image
WV01 - December 9, 2009
Projection: Nepal Albers Equal Area conic

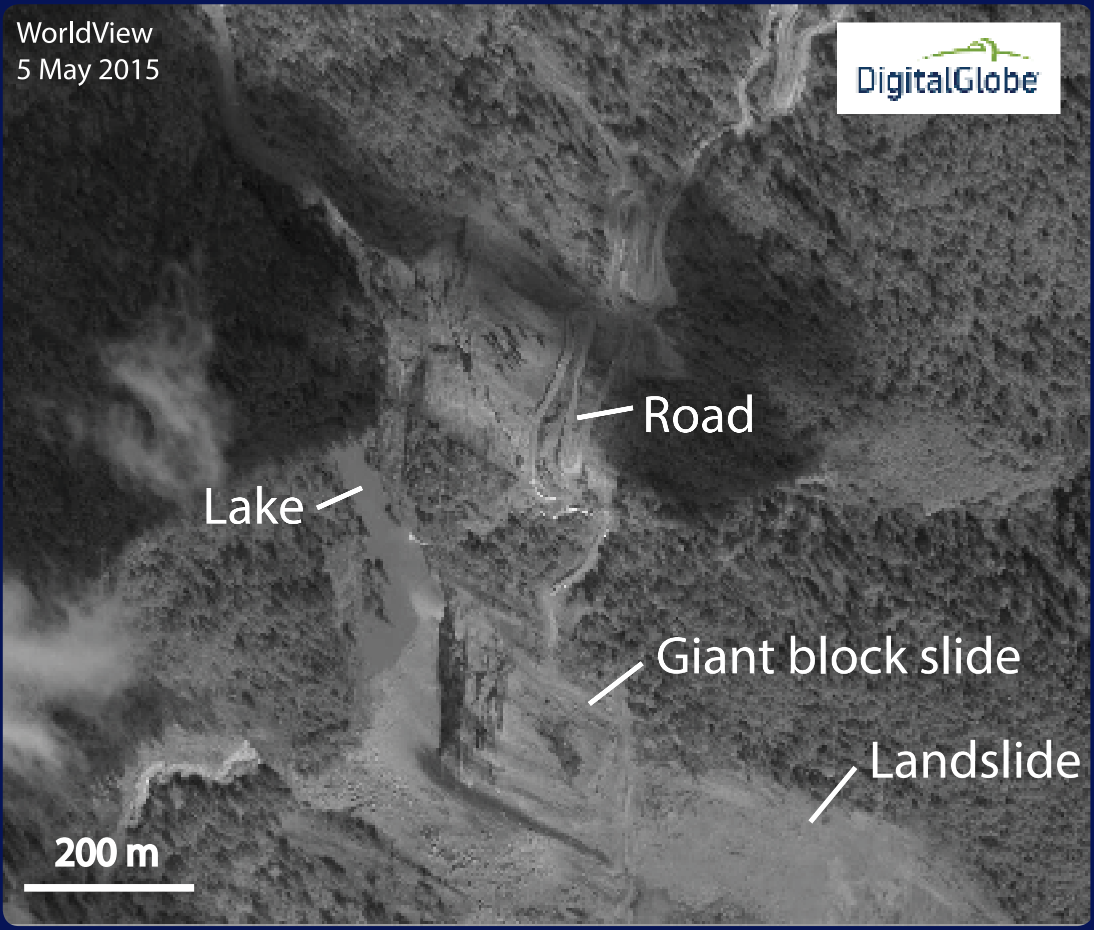
SPOT 6 panchromatic image
SPOT6_MS_20154270436344_ORT_1281790101 - April 27, 2015
Projection: Nepal Albers Equal Area Conic

Source: WorldView 1 from 9 December 2009, and SPOT 6 from 27 April 2015

Figure 22: **Shallow landslide temporarily blocking the Sun Koshi River about 1 km downstream from Chaku village**

Source: WorldView 02 image); left, pre-earthquake (Google Earth image, 12 April 2014); right, post-earthquake (WorldView 02 image, 3 May 2015)

Figure 23: **Large landslide blocking the road and damming the Trishuli River at Chongsecun 7 km north of the China/Nepal border**



Source: Landsat 8 image, 30 April 2015; analysis by University of Cambridge and ETH, Zurich

Sun Koshi River, Chaku village

The Sun Koshi River was blocked by a landslide about 1 km downstream from Chaku village in Sindhupalchok at 27.879°N, 85.900°E (Figure 22). The landslide was shallow but sufficient to temporarily block the river; the dam was released in less than a day.

Trishuli River

A large landslide (800 x 200 m) crossed a road and dammed the Trishuli River (also known as the Gyriong Zangbo) at Chongsecun 7km north of the China/ Nepal border (~2,600 masl) at 28.359°N, 85.365°E (Figure 23). A lake approximately 100 m wide and 500 m long had formed by 30 April 2015. The lake was considered to pose a high risk if the dam breached, with a potential for downstream flooding, but then drained naturally without causing damage.

Three more landslide dams, 5.5 and 4 km apart, formed downstream along the same river in Haku VDC, Rasuwa, along the route to Langtang village. None of the dams had a major impact as the impoundment was released naturally (Figure 24).

Figure 24: **Landslide dams along the Trishuli River in Haku VDC, Rasuwa**

Source: DigitalGlobe, 3 May 2015

Baisari landslide dam (Kali Gandaki River, Myagdi District)

On 24 May 2015, a rock slide of approximately 350 x 200 x 4 m^3 buried Baisari village in Myagdi (28.400° N, 83.583° E) under about 30 m of debris and blocked the Kali Gandaki River (Figure 25). Cracks formed in the cliff following the 25 April earthquake and widened during the strong tremor of May 12. Rocks began falling from the cliff ten days later on 22 May. The Nepal Army evacuated Baisari village and the cliff failed two days later at about 1:00 am on 24 May. The landslide destroyed 27 homes and buried the entire village under the debris. A 2.7 km long and 100 m wide lake formed impounding ~8,000,000 m^3 of water (Collins and Jibson 2015). The lake overtopped the dam 16 hours after it formed and sent a flood-wave down the Kali Gandaki River; water levels reportedly rose temporarily to 2 m above the normal monsoon level. Fortunately, the communities downstream of the landslide dam had been evacuated, and no loss of life occurred.

CAS reported four more locations where the Kali Gandaki River appears to have been partially blocked based on analysis of pre-earthquake (Google Earth 12 December 2014) and post-earthquake (GF-1, 1 May 2015) images. The landslides formed small lakes of around 0.2 to 0.3 km^2.

Other landslide dams

Some of the other landslide dams identified are described in Table 12. Collins and Jibson (2015) identified 69 landslide dams, but also noted that many more probably occurred. Even so, the total number is small compared to the total number of landslides and most of them were small in size and impact.

Figure 25: **The rock slide along the Kali Gandaki River from 24 May 2015 that buried the village of Baisari and blocked the flow of the river for 16 hours showing the lake impoundment on 29 May 2015 after breaching**

Table 12: **Other landslide dams**

River	Location	Impact	Damage
Tadi (tributary of the Trishuli)	Near Sikharbesi village in Nuwakot at 27.983°N, 85.400°E	Small landslide blocked the river	None
Trishuli	Opposite Ramche village in Rasuwa from Dandagaon to Shyfru Besi	Many scars developed as gullies a few metres to several hundred metres long along the right bank of the Trishuli River. The gullies deposited debris which partially blocked the river at four places.	Road to Melung hydropower damaged
Daraudi	About 5 km upstream of Ghyachok in Rasuwa at 28.296°N, 84.729°E	Debris from a landslide filled the river valley, temporarily blocking the river, but there was no evidence of the river being dammed.	None
Budhi Gandaki	Along the trekking route to Manaslu near Samagaun (Samdo) in Manang at 84.634°E, 28.633°N	A small avalanche blocked the river	Not known

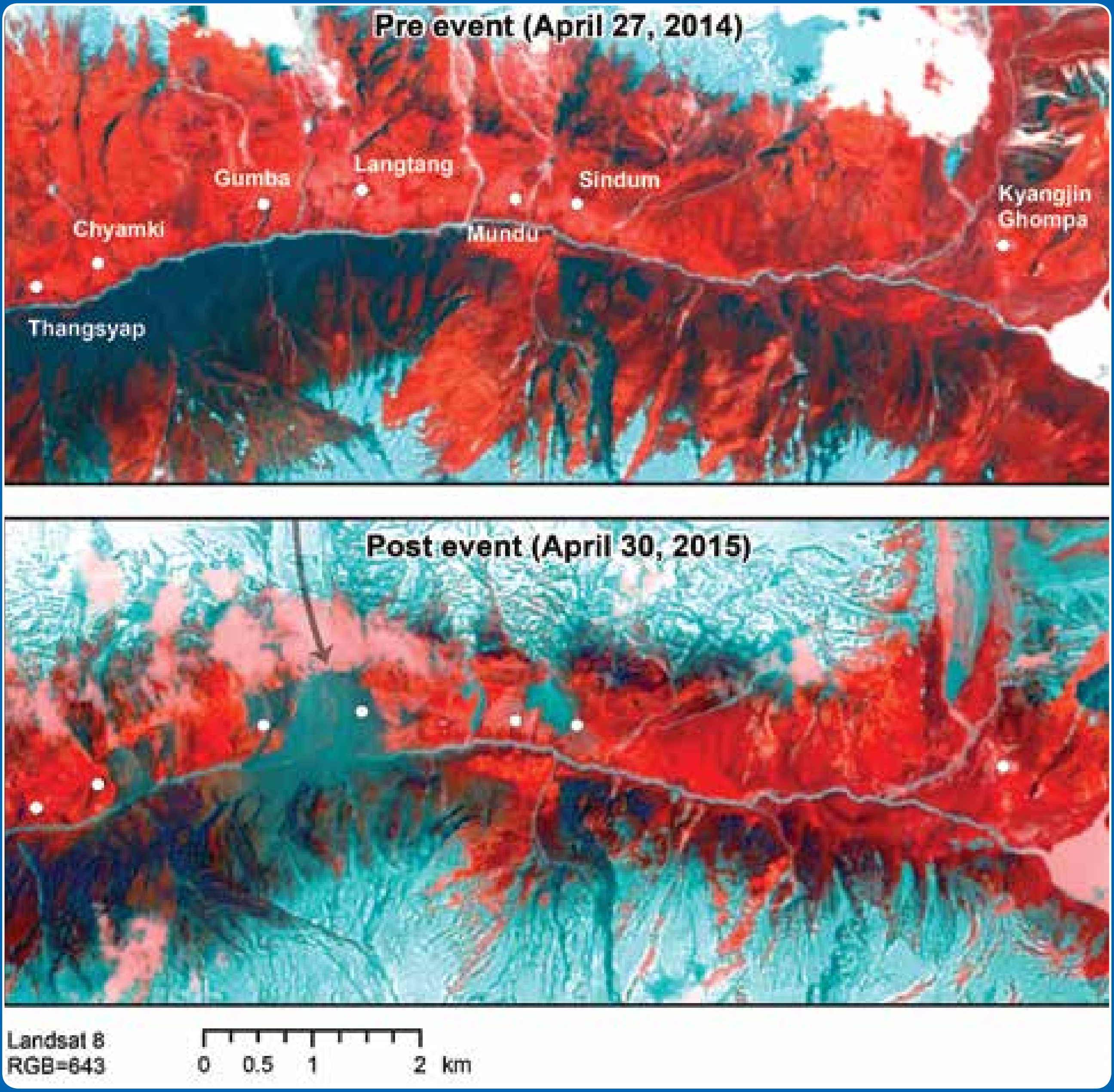
Earthquake-Induced Avalanches

The earthquake of 25 April induced two disastrous avalanches, one in Langtang valley, Rasuwa, and another at Everest Base Camp, Solukhumbu.

Landslide/avalanche in Langtang

The most destructive and probably the largest landslide triggered by the 2015 earthquake was a massive landslide/avalanche initiated near 7,000 masl which completely buried Langtang village and deposited materials (ice, rock and soil) across the Langtang River. Kargel et al. (2016) estimated that the ice-snow avalanche initiated near 7,000 m elevation with entrained rockfall material and descended along a low-gradient part of the glacier to ~4,500 masl, from where the rock-ice mass became airborne down to the riverbed at ~3,250 masl. A study by Lacroix (2016) based on analysis of digital elevation models estimated the deposit at 7 million cubic metres, more

Figure 26: **Langtang village is completely buried under the landslide debris**



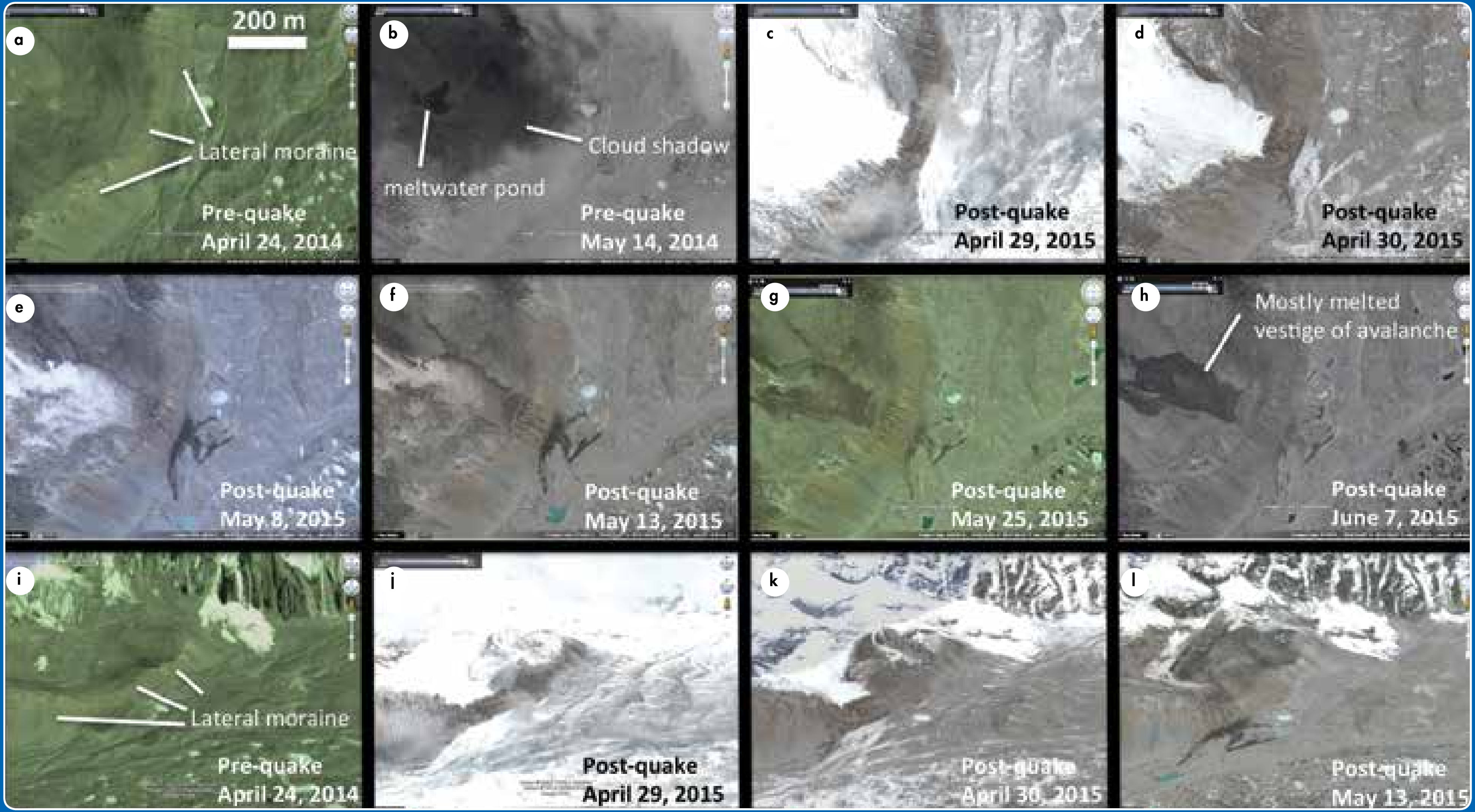
Source: Landsat 8; analysis by W.W. Immerzeel and P.D.A. Kraaijenbrink, Utrecht University

than half of which could have been ice. The pre- and post-earthquake images show Langtang and Gumba villages completely buried under the debris (Figure 26). The river apparently melted the ice deposited in the river channel and the water flowed through a tunnel which formed in the ice and debris. The 25 April avalanche/landslide was followed by another similar size landslide around 8 to 10 May. There were more than 300 estimated fatalities. There was no evidence of lake formation upstream of the landslide.

Everest Base Camp

Everest Base Camp was also hit by an earthquake-induced ice avalanche, even though shaking at this point was light. The tremor on 25 April 2015 unleashed what was probably a hanging glacier (Figure 27). The collapsing icy mass swept away a part of Everest Base Camp, and with it 22 lives. It was the worst single day in the history

Figure 27: **Earthquake triggered ice and snow avalanche onto the Khumbu glacier near Everest Base Camp; images from DigitalGlobe and CNES/Astrium rendered in Google Earth. Top panels show an ortho view zoomed in to the tongue of one avalanche where it spilled over the lateral moraine and onto the Khumbu glacier; A and B are pre-quake images taken about a year before the earthquake. C through H are post-quake images obtained in 2015 showing the rapid melting of the avalanche. The bottom panel is an oblique rendering of this and other avalanches with prequake and post-quake images. 28.012°N, 86.833°E**



of Everest and occurred a year after the previous worst day in the mountain's history (18 April 2014), when ice avalanches hit the Everest climbing route over the Khumbu glacier killing 16 Sherpa porters and guides.

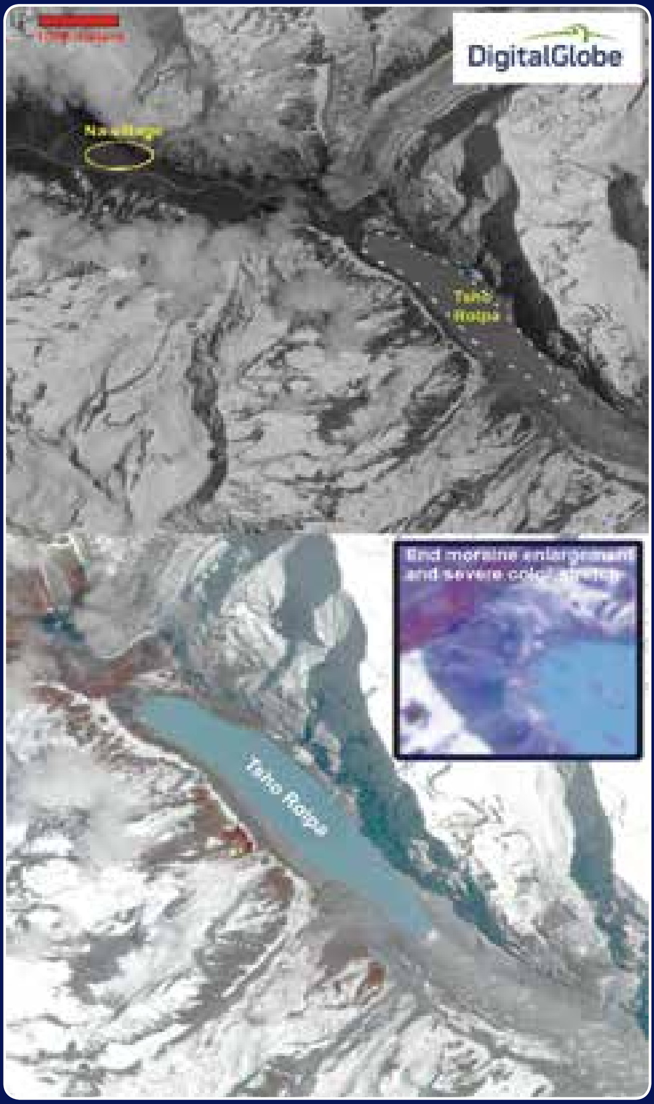
The indication is that ice was poised on the mountain ready to collapse. Springtime melting triggered the collapse in 2014 and probably conditioned the ice for collapse in 2015 so that only a light shaking was needed to break it loose (calculated peak ground acceleration only 0.08 g).

Risk Assessment of Potentially Dangerous Glacial Lakes

After the two major tremors on 25 April and 12 May, scientists and authorities from Nepal, USGS, and the NASA and University of Arizona led international volunteer-group of satellite image analysts examined the condition of more than 300 potentially dangerous glacial lakes. Alton Byers led a team on a field visit to selected lakes and a USGS team led by Bryan Collins made a helicopter survey of the lakes. Later, a team from ICIMOD with Jeffrey Kargel carried out an aerial survey of the lakes and made selected field visits. The following presents a synthesis of the various efforts made to understand the impact of the earthquake on the integrity of the lakes and potential glacial lake outburst floods (GLOF). The overall conclusion is similar, to the best of our knowledge, based on remote sensing analysis, field visits, and aerial observation, the earthquake did not cause any GLOFs and not result in any additional, definitive risk for future GLOFs. This was both fortunate and surprising. The good news, however, does not necessarily indicate that future earthquakes will have a similarly low impact, as they could strike closer to and more directly beneath the glacial lakes, and the resultant strong seismicity could trigger large landslides or avalanches into the lakes or directly undermine the structural integrity of the moraine dams, thus unleashing GLOFs.

Figure 28: **Satellite images of Tsho Rolpa lake:**

a) DigitalGlobe image from January 2015; b) EO-I ALI image from 17 May 2015



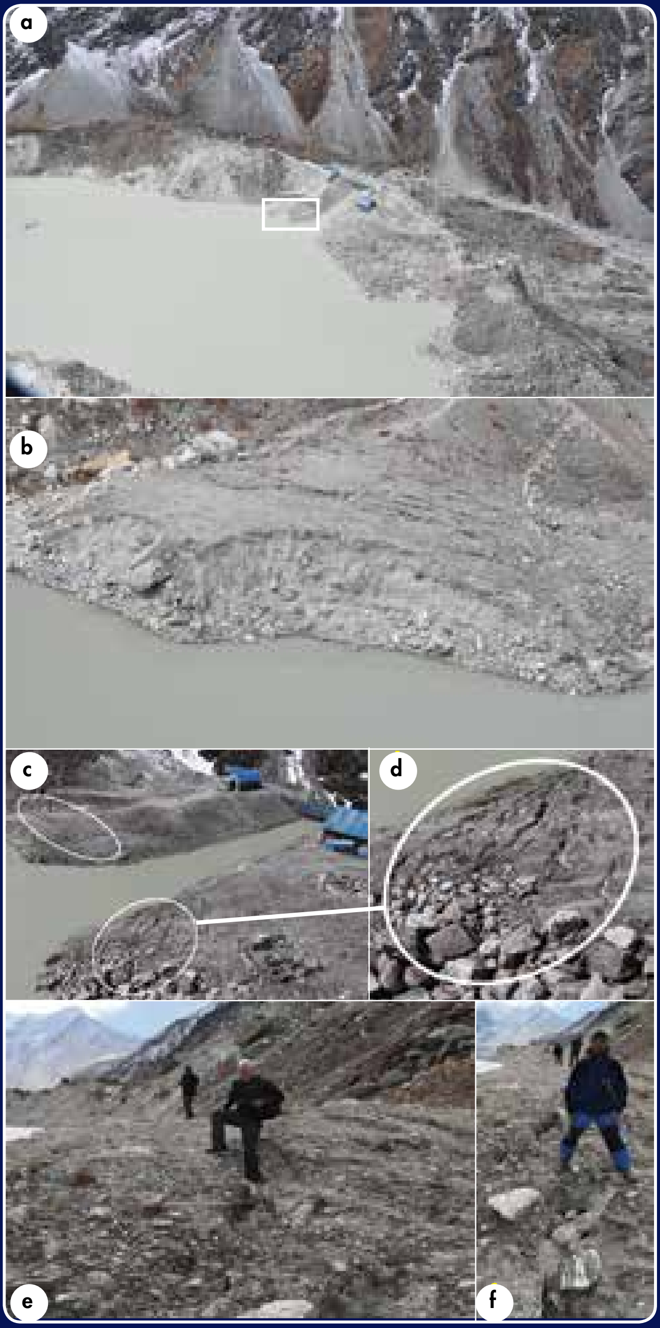
Tsho Rolpa lake

Satellite images of Tsho Rolpa from NASA's EO-1 satellite and instrument ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) aboard the NASA Terra satellite from 17 May – five days after the nearby M7.3 aftershock – show no evidence of damage to Tsho Rolpa's moraine or other parts of the glacier or lake (Figure 28). The 10 m resolution of the EO-1 image and 15 m resolution ASTER image do not permit detailed assessment of structural features smaller than that, but what can be seen does not elicit new concerns about the potential for a GLOF, and these new observations erased some of the fears that heavy damage could have been incurred. There were no obvious new drainage paths and no large landslides into the lake could be discerned. The discernible differences in the pre- and post-earthquake images (Figure 28) are primarily related to changes in seasonal snow cover.

The remote sensing-based interpretation was corroborated by various aerial observations including those by USGS and ICIMOD. Photographs taken from a helicopter on 21 May 2015 and released by a Nepali newspaper (www.pahilopost.com/content/-4309.html) show no visible disturbance to the moraine dam or the engineered structures used to lower and control the lake level. Both the satellite images and these aerial photos show that the lake was still well-contained within the moraine dam. This was further corroborated by a photo taken on 27 May 2015 during a helicopter mission organized by USGS, which showed the moraine to be intact as far as could be seen. Additional aerial and ground-based photos were obtained by an independent citizen, Saroj Dhoj Joshi, and made available for the research (http://web.hwr.arizona.edu/GLIMS/2015-TshoRolpaNepal-Photos-SarojDhojJoshi.zip). These photos show the hazardously poised lateral moraine and adjacent mountain slopes, yet they also show no indication of recent disturbances caused by the earthquakes. This work is an example of how satellite imaging, expert knowledge, and 'citizen science' can work together to contribute to discussions of public safety in the aftermath of a natural disaster.

Figure 29: **Tsho Rolpa lake:**

a) The artificial outlet; b) close view of the right bank of the inlet to the artificial outlet indicated by the rectangle in a); c) cracks on the banks of the inlet (source USGS); d) detailed view of cracks in the right bank of the inlet shown by the ellipse in the bottom part of c; and e, f) detailed view of the cracks indicated by the ellipse in the top part of c)



The observations did reveal the formation of cracks in the moraine (Figure 29). USGS scientists Bryan Collins and Randall Jibson observed fractures with a fresh appearance in the end moraine dam in July 2015, and considered that they were probably related to shaking of the engineered surface close to the artificial outlet. They suggested that the cracks were the result of surficial lateral spreading in cohesive sediments and not indicative of larger failure at depth. This could be confirmed in future studies using a geophysical imaging campaign to see if densities or water contents below this section are different to those in the non-cracked areas. During a brief field visit on 28 October 2015, the authors of the present study found that the fractures had degraded during the monsoon months (Figure 29e,f). One point of concern was that the fractures seemed to have some roots in the engineered moraine material, and micro-cavern development had been taking place. However, the field research team considered that the fractures are unlikely to indicate any great damage. Because this part of the moraine does not contain ice, the cracks are unlikely to induce a failure of the moraine dam. Rather, they may imply a relatively mild slumping of some moraine material towards the lake. However, there is still a lack of information about how the deeper structure of the moraine may or may not have been affected by the earthquake. Further investigation of this, and remediation of any problems at an early stage, is necessary.

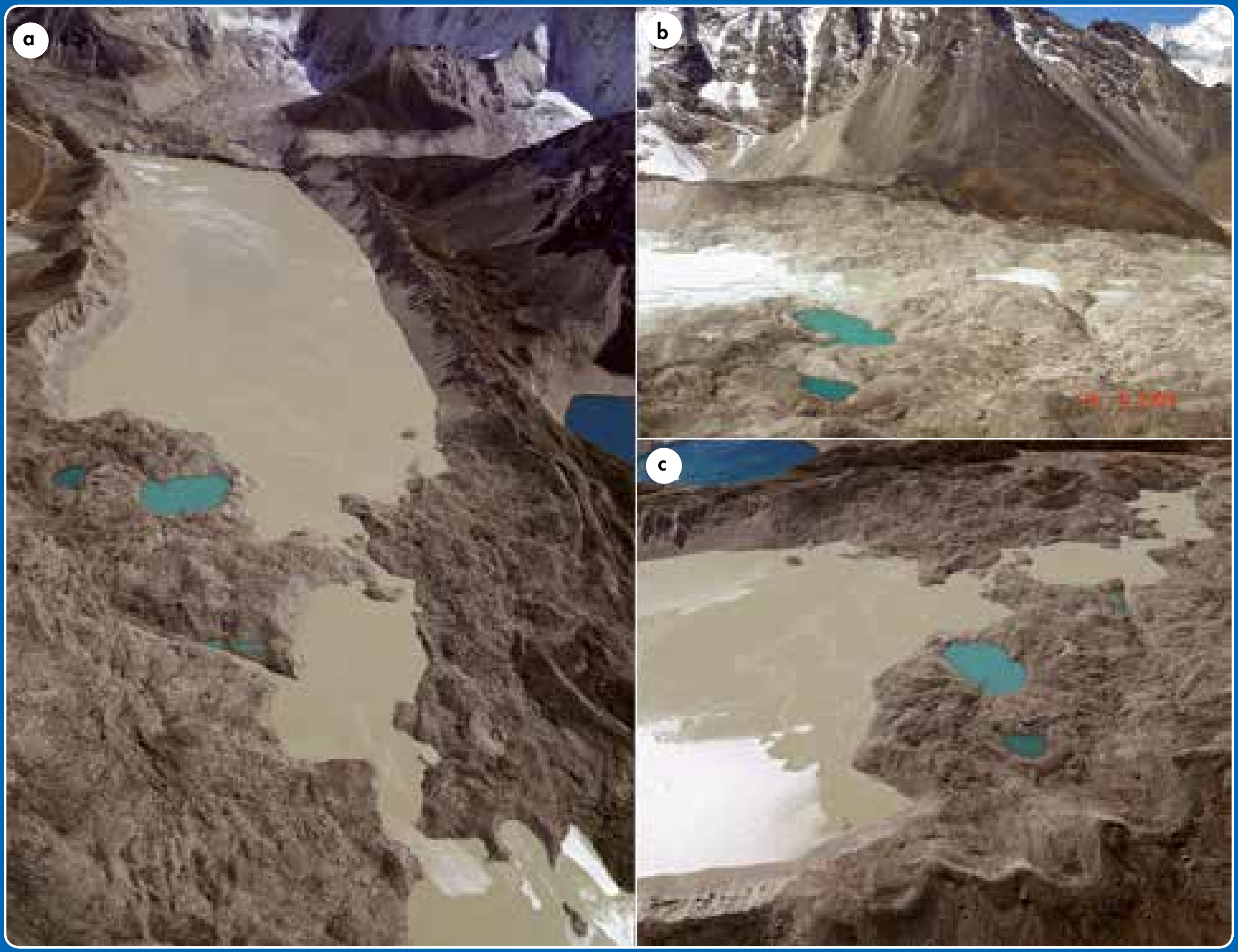
There have been long-running concerns about the safety of Tsho Rolpa. A hazard mitigation project 15 years ago successfully lowered the lake level, which has helped reduce the possible impacts in the event of a GLOF (Figure 29). A GLOF early warning system based on meteoburst technology was installed during the project but was rendered dysfunctional as a result of vandalism and a lack of maintenance during the insurgency period, mainly between 2000 and 2005. Following the Gorkha earthquake, the authorities recognized the importance of the issue and the heightened anxieties of residents and a new automatic GLOF-warning system was installed (www.ekantipur.com/2015/05/21/national/early-warning-system-installed-in-tsho-rolpa/405485.html). The new system will alert the authorities, who can alert residents of downstream villages such as Na in the event of a GLOF or a precursor event.

Imja lake

Figure 30 shows the end moraine of Imja glacial lake. Comparison of the images from 2009 and after the earthquake in 2015 (Figure 30b,c) shows that the moraine has undergone significant change, particularly related to the dynamics of the outlet channel. However, this is considered to be independent of the earthquake.

A report was widely circulated on social media that a small GLOF may have occurred on 24 May in the vicinity of Imja lake. Residents reported a loud sound heard several kilometres away – possibly from Lhotse glacier (south of Everest) – which was followed by a transient, anomalous rise in stream level. However, there is no evidence that points towards Imja Lake as the source. Instead, the event is thought to have resulted from ice fracturing and a small supraglacial pond draining from Lhotse glacier. This is the only possible GLOF reported from the region in the weeks following the Gorkha earthquake. It caused alarm but no damage, and may have been related more to spring melting than to the earthquake.

Figure 30: **a) Aerial view of Imja lake; b) end moraine and outlet channel of Imja lake in 2009; and c) similar view in October 2015 after the earthquake**



Lakes in Tibet Autonomous Region

Satellite images of lakes in Tibet Autonomous Region (TAR) of China, just across the border from Tsho Rolpa, also show no evidence of outburst floods or major damage to their moraines (Figure 31). The Chinese Academy of Sciences (CAS) is tracking the effects of the earthquake in TAR. Although many landslides occurred there, the moraine dams of the glacier lakes checked by the CAS team appear to have been unaffected by the quake. The red dots in Figure 31 identify lakes that appear completely unchanged from their state just prior to the earthquake.

According to some local residents, there may have been two small GLOFs during the weeks after the main shock. One possibility is that these lakes emitted small frightening, but otherwise harmless, floods due to discharges from supraglacial ponds, and that these emissions were in some way conditioned by the earthquake. Equally, these GLOFs might have occurred due to spring melting; similar small GLOFs occur frequently, especially in spring and summer.

Overall status

Of the 489 glacial lakes surveyed by the two groups utilizing satellite images – Nagoya University and University of Dayton – only nine showed any evidence of effects caused by the earthquake (Kargel et al. 2016). These nine lakes showed what appeared to be landslides striking them (but without outburst). The best documented case of probable earthquake damage to a glacial lake was at Tsho Rolpa (Figure 29), but the cracks observed in the end moraine dam were not thought to be serious. Other lakes, including Imja, showed no indication of earthquake damage when viewed either by satellite or by a helicopter.

The situation of Himalayan glacial lakes needs to be observed carefully in China, India, and Nepal to confirm the preliminary conclusions that the GLOF risk has not been visibly heightened by the earthquake. There are many glacial lakes in the Himalayas, many of them extremely hard to reach. Thus satellite imagery has to be used to

Figure 31: **Lakes in TAR, China just across the border from Tsho Rolpa. The red dots identify lakes that appear completely unchanged from their state just prior to the earthquake**

Source: EO1 image of 17 May, 2015

inspect most of the region's glacial lakes. However, detailed assessments using aerial surveys and ground-based observations are needed to verify that no damage has been done at a scale smaller than the resolution of the satellite images, particularly for the selected priority glacial lakes.

Summary and Conclusions

- The main geohazards induced by the 2015 Gorkha earthquake were landslides, river channel constriction and damming, and avalanches with debris flow and airburst.
- The Gorkha earthquake and associated aftershocks resulted in considerable loss of life, especially in some remote Himalayan valleys, but the damage due to landslides and glacier lake outburst floods was less than anticipated. The number of landslides was large, but much less than that induced elsewhere by other earthquakes of similar magnitude.
- Landslides occurred mainly on steep slopes, in areas with strong shaking, near ridge crests, in the tectonically down dropped blocks, in certain lithologies, and near lithological contacts or interbedding.
- The geohazards were confined to specific physiographic regions and specific areas. Landslides and river channel constriction and damming are mostly confined to the high mountain areas
- Landslides are common geomorphic processes in mountain areas and many existed before the earthquakes. Many co-seismic landslides occurred in areas of forest and shrubland originating from the upper slopes (near ridges) and initiated by rock falls.
- The observations indicate that wave interactions with complex topography caused a general enhancement of shaking on or near ridge crests but had less impact on valley bottoms where lakes occur. The number and density of landslides appeared to be very sensitive to the amount of shaking; a slightly greater seismic disturbance might well generate a disproportionately much larger number of landslides.
- The main effect of the shaking was collapse of buildings (private and public) and cracking of land and roads. The earthquake-induced geohazards also led to loss and damage of buildings, particularly in newly-developed settlements along the highway, and cultivated land, but in addition there was a marked impact on standing crops and infrastructure such as bridges, trails, roads, hydropower projects, and irrigation canals. The secondary effect of the damage from geohazards is likely to be comparatively much higher than that of the direct earthquake impact in terms of loss of livelihoods, blocking of movement of people, goods, and services, and loss of revenue from trade and energy supply.
- Many of the landslides and landslide dams, and the possibly increased instability of glacial lakes, have the potential to lead to a chain of hazards such as debris flows and outburst floods with loss of life, property, and infrastructure in the future.
- Many institutions were involved in mapping landslides in the earthquake-affected area. The reported number of co-seismic landslides was more than 4,000, however, there are a number of methodological and subjective issues involved in identifying and mapping co-seismic landslides including the quality and resolution of satellite images and date of acquisition, and the approach and methods of used to map landslides (e.g., point/polygon/multi-tongued landslide as one unit or separate units/whether the activated gullies are mapped).
- The NPC estimated the disaster effects from the earthquake(s) by sector at district level in its PDNA report, but there is only a limited amount of information about the disaster effects from the different types of earthquake-induced geohazards at community, VDC, and district levels.
- The absence of any large GLOFs following the Gorkha earthquake and aftershocks was very fortunate but should not be overly interpreted as assuring a similar absence following any future large earthquake.
- The high pent-up stresses known to exist in much of the Himalayan arc have been partly relieved over the section where this major earthquake occurred. However, the stress relief was insufficient to greatly reduce the likelihood of another large earthquake occurring in the future, and the relatively limited damage done by this earthquake should not be taken as indicating that the damage from a possible future large earthquake would be similarly low.

Recommendations

- Direct shaking damage due to earthquakes and damage from earthquake-induced geohazards need to be treated separately since their nature and effects and mitigation and adaptation options are different. A multi-hazard risk assessment and management approach should be developed and adopted that takes this into account.
- Detailed mapping of geohazards and assessment of risk should be carried out using both remote sensing techniques and community-based methods.
- Identification and implementation of effective mitigation and adaptation measures should be undertaken involving all key stakeholders
- Land use guidelines and building codes should be developed and implemented with the aim of limiting exposure to geohazards and paying more attention to areas where major infrastructure development projects (roads, hydropower, and others) are proposed.
- Detailed geophysical model simulations should be developed to show seismic wave propagation and surface interactions from the Gorkha earthquake and other potential future large earthquakes to build a better understanding of how future earthquakes may differ in effects from the Gorkha earthquake.
- Systematic collection, recording, and archiving of the losses and damage from earthquake-induced geohazards should be carried out.
- A system for monitoring and communicating the risk of geohazards should be developed.
- Detailed landslide impoundment and landslide dammed lake outburst flood modelling should explore critical vulnerabilities and approaches to hazard mitigation and disaster response.
- The capacity for assessing and managing the risk of geohazards should be developed and strengthened.
  - Improve awareness of and access to geospatial data, products, and tools related to multi-hazard risk assessment and management among government agencies, academia, and organizations providing information services.
  - Provide additional geospatial data, products, and tools to inform decision making on multi-hazard risk assessment and management.
  - Improve the capacity of analysts and decision makers to use Earth observations and geospatial technology. Capacity needs must be identified and defined through needs assessments and formal engagements among decision makers and scientists.
  - Identified capacity needs can inform training programmes and the design of custom information services.
  - Build institutional capacity of decision-making agencies, national and international information service providers, and the academic sector to increase the appropriate use and demand of such information.
- Detailed assessments of climate- and demographic-change scenarios and their impacts on natural hazards should be undertaken to enable a better understanding of how future disasters and their potential impacts on lives and livelihoods may shift.

References

Collins, BD; Jibson, RW (2015) *Assessment of existing and potential landslide hazards resulting from the April 25, 2015 Gorkha, Nepal Earthquake Sequence (ver. 1.1, August 2015): U.S. Geological Survey Open-File Report 2015-1142*. Menlo Park, CA, USA: U.S. Geological Survey. http://dx.doi.org/10.3133/ofr20151142

Costa, JE; Schuster, RL (1988) 'The formation and failure of natural dams.' *Geological Society of America Bulletin* 100: 1054-1068

Costa JE; Schuster RL (1991) *Documented historical landslide dams from around the world*. U.S. Geological Survey Open-File Report 91-239. Washington, USA: United States Department of the Interior. Available at http://pubs.usgs.gov/of/1991/0239/report.pdf (accessed 22 April 2016)

DRR Portal Nepal (2015) *Nepal Earthquake 2015: Disaster Relief and Recovery Information Platform (NDRRIP)*. http://drrportal.gov.np/ (accessed 9 December 2015)

Evans, SG; Hermanns, RL; Strom, AL; Scarascia, MG (eds) (2011) 'Natural and artificial rockslide dams, lecture Notes in Earth Sciences. *Springer*, Heidelberg

Girty, GH (2009) *"Landslides", Perilous Earth: Understanding Processes Behind Natural Disasters*. Montezuma Publishing, pp. 1–1

Götz, J; Weidinger, JT; Kraxberger, S; Hennecke, A-L; Buckel, J; Adikhari, BR (2015) 'Geomorphologic and hydrogeologic characteristics of populated rockslide deposits (Sagarmatha National Park, Khumbu Himal, Nepal).' *Journal of Water Resources and Protection* 7: 1038-1048

IPPAN (2015) *Hydropower projects affected by Gorkha earthquake*. Kathmandu, Nepal: Independent Power Producers Association Nepal

Jibson, RW (2011) 'Methods for assessing the stability of slopes during earthquakes – a retrospective.' *Engineering Geology* 122(1/2): 43–50. doi:10.1016/j.enggeo.2010.09.017

Kargel, JS; Leonard, B; Crippen, RE; Delaney, KB; Evans, SG; Schneider, J (2010) Satellite monitoring of Pakistan's rockslide-dammed Lake Gojal.' *Eos, Transactions American Geophysical Union* 91(43). doi:10.1029/2010EO430002.

Kargel, JS; Leonard, GJ; Shugar, DH; Haritashya, UK; Bevington, A; Fielding, EJ; Fujita, K; Geertsema, M; Miles, ES; Steiner, J; Anderson, E; Bajracharya, S; Bawden, GW; Breashears, DF; Byers, A; Collins, B; Dhital, MR; Donnellan, A; Evans, TL; Geai, ML; Glasscoe, MT; Green, D; Gurung, DR; Heijenk, R; Hilborn, A; Hudnut, K; Huyck, C; Immerzeel, WW; Liming Jiang; Jibson, R; Kääb, A; Khanal, NR; Kirschbaum, D; Kraaijenbrink, PDA; Lamsal, D; Shiyin Liu; Mingyang, LV; McKinney, D; Nahirnick, NK; Zhuotong Nan; Ojha, S; Olsenholler, J; Painter, TH; Pleasants, M; KC, P; Yuan QI; Raup, BH; Regmi, D; Rounce, DR; Sakai, A; Donghui Shangguan; Shea, JM; Shrestha, AB; Shukla, A; Stumm, D; van der Kooij, M; Voss, K; Xin Wang; Weihs, B; Wolfe, D; Lizong Wu; Xiaojun Yao; Yoder, MR; Young, N (2016) 'Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake.' *Science* 351 (6269) DOI: 10.1126/science.aac8353. Available at http://science.sciencemag.org/content/351/6269/aac8353

Lacroix, P (2016) 'Landslides triggered by the Gorkha earthquake in the Langtang valley, volumes and initiation processes.' *Earth, Planets and Space* 68:46

Newmark, NM (1965) 'Effects of earthquakes on dams and embankments.' *Geotechnique* 15: 139–159

NPC (2015a) *Post disaster needs assessment, Vol. A: Key findings*. Kathmandu, Nepal: Government of Nepal, National Planning Commission

NPC (2015b) *Post disaster needs assessment, Vol. B: Sector reports*. Kathmandu, Nepal: Government of Nepal, National Planning Commission

Parker, RN; Hancox, GT; Petley, DN; Massey, CI; Densmore, AL; Rosser, NJ (2015) 'Spatial distributions of earthquake-induced landslides and hillslope preconditioning in the northwest South Island, New Zealand.' *Earth Surface Dynamics* 3: 501–525 DOI:10.5194/esurf-3-501-2015

Peng M; Zhang LM (2012) 'Analysis of human risk due to dam break floods – Part 1: A new model based on Bayesian networks.' *Natural Hazards* 64(2):1899–1923

Schuster, RL (1993) 'Landslide dams – a worldwide phenomenon.' In *Proceedings Annual Symposium of the Japanese Landslide Society, Kansai Branch, 27 April, Osaka*, pp1–23

Schuster, RL (1995) 'Landslide dams – a worldwide phenomenon.' *Journal of the Japanese Landslide Society* 31(4): 38–49 (in Japanese)

Schuster, RL; Costa, JE (1986) 'Effects of landslide damming on hydroelectric projects.' In *Proceedings 5th International Association of Engineering Geology Congress, Buenos Aires* 1986, pp 1295–307

Schuster, RL; Wieczorek, GF; Hope II, DG; Keefer, DK (1998) *Landslide dams in Santa Cruz County, California, resulting from the earthquake*, U.S. Geological Survey Professional Paper 1551-C, pp 51–70. Washington DC, USA: U.S. Geological Survey

Sharma, E; Shrestha, AB (2015) 'Nepal 2015 Earthquake: Uncertainty prevails in the Himalayan Arc.' *Proceedings of Indian National Science Academy* 81: 557–560

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