Research Paper

Landslide dams and their hazard after the 25 April 2015 Gorkha Earthquake in Central Nepal

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ABSTRACT

Large landslide dams are one of the most destructive natural phenomena. They frequently occur in tectonically active orogenic belts with narrow and steep valleys. Nepal hosts many large landslide dams, some of which must have been caused by past earthquakes. The Mw 7.8 Gorkha Earthquake of 25 April 2015 and its aftershocks triggered off many shallow failures with only a few landslide dams that were either very short-lived or only partially blocked the river course. The area affected by the earthquake belongs to the Lesser Himalayan Sequence, Higher Himalayan Crystallines, and the Tethyan Himalayan Sequence. The severely affected area is made up of such resistant rocks as quartzites, gneisses, granites, marbles, and schists. These rocks have generally three discontinuity sets, which are almost perpendicular to each other. A detailed analysis of dip slopes, anti-dip slopes, and dip-normal slopes in the earthquake-affected area revealed that the dip-normal slopes were the most vulnerable ones. Many rockslides and rock falls began from the crest and created long runout paths.

The potential sites of landslide damming can be inferred by analysing morphometric parameters together with seismic, geological, hydro-meteorological, and anthropogenic factors. Such damming sites were identified heuristically at various locations of the major rivers, based on the criteria discussed above. Since the earthquake-triggered failures were concentrated mainly on steep slopes with a high internal relief, a hazard map was prepared by combining the safety factor map with the slope map and the internal relief map. There is a good correspondence between the high hazard zones and the heuristically identified potential sites of landslide damming.

1. Introduction

Large landslide dams are one of the most disastrous natural phenomena in mountainous regions all over the world (Schuster and Costa, 1986; Costa and Schuster 1988, 1991; Evans et al., 2011). Such dams are formed most commonly in tectonically active settings where high mountains border narrow and steep valleys and earthquakes occur frequently. Landslide dams are very diverse in terms of their formation, geotechnical

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characteristics, longevity, stability, and flood hazard. The two major causes of landslide dam formation are precipitation and earthquake. About 50 % of dam-forming landslides are brought about by rainstorms and snowmelts, 40% by earthquakes, and 10 % by other factors (Schuster, 1993; Peng and Zhang, 2012). Geometry of valley in relation to geometry and volume of debris and discharge of damming river are some of the factors which are responsible for the development of landslide dams. Schuster et al. (1998) mentioned four groups of governing factors responsible for the spatial distribution of landslide dams. They are i) seismic intensity, ii) slope gradient and topography, iii) lithology and weathering properties, and iv) soil moisture and groundwater content.

Landslide dams are generated by various types of mass movements, which range 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.

The lifespan of a landslide dam varies widely from several minutes to several thousand years. When a dam is formed, it is very difficult to predict when or whether it fails. Consequently, understanding how the characteristics of landslide dams influence the peak outflow of resulting dam-break floods are of critical importance in effective hazard management. Managing landslide-dam hazards requires an understanding of the temporal and spatial scales on which such phenomena occur. Many previous works on landslide dams have been mainly descriptive in character, and have produced a multitude of documented case studies and inventories (e.g. Costa and Schuster, 1988; Costa and Schuster, 1991). More recent work is focused on quantitative methods of determining the post-formation development, in particular, the controls on dam longevity (Schuster, 2000; Manville, 2001; Ermini and Casagli, 2003; Korup, 2004, 2005).

Landslide-dammed lakes may survive for varying periods, depending on such factors as volume, size, and shape of the dam and sorting of its constituents. The lifespan of the dam also depends on sedimentation rate and water inflow to the lake. According to a worldwide statistics (Costa and Schuster, 1988), 27 % of landslide dams (n = 73) fail within one day of formation, 41 % within one week, 56 % within one month, and 85 % within one year. Landslide dams may fail by different failure modes based on material properties of the dam body and stream channel conditions. They may fail by the erosive destruction due to overtopping, abrupt collapse of the dam body, or progressive failure (Takahashi, 1991).

2. Geological setting

The Himalayan Range was formed as a result of collision between Indian plate and Eurasian plate about 40 or 50 million years ago. The collision led to the large crustal shortening, resulting into the formation of the Himalaya. The mountain-building process still ongoing. This youngest mountain range in the world is convex southwards and extends for over 2400 km in an east–west trend.

The 25 April 2015 earthquake-affected area can be divided into the Lesser Himalayan Sequence, Higher Himalayan Crystallines, and the Tibetan–Tethyan Sediments (Dhital, 2015). These rocks have been classified into various formations (**Fig. 1**) and a short description of them is given below.

The Lesser Himalayan Sequence begins with the Kuncha Formation phyllites, metasandstones, and schists with a few bands of quartzite and intrusives, including some nepheline syenites. This formation is succeeded by the Fagfog Quartzite, Ghandruk Quartzite, or Birethanti Quartzite. These quartzite bands are resistant, have light yellow to white colour, and have a thickness of several hundred metres. The quartzite unit is then followed up-section by the variegated schists, slates, and carbonates named as the Dandagaon Phyllites, Nourpul Formation, or Lower and Upper Schists. Further stratigraphically upwards are found gray dolomites and slates with columnar stromatolites, belonging to the Dhading Dolomite. This unit is succeeded upwards by black Benighat Slates and grey limestones with Jhiku carbonates and Malekhu Limestone. The topmost unit of the Lesser Himalayan Sequence is represented by slates, schists, amphibolites, and quartzites.

The Higher Himalayan Crystallines override the Lesser Himalayan Sequence along the Main Central Thrust. They are made up of schists, gneisses, and quartzites (Formation I), some marbles and gneisses (Formation II) intruded by Palaeozoic and Miocene Granites. Formation III is represented by calcareous schists, marbles, and augen gneisses. In the Kathmandu area, the Tethyan Himalayan Sequence is classified into the Tistung Formation (biotite schist and quartzite) followed by the Sopyang Formation (limestone and slates), the Ordovician Chandragiri Limestone, Chitlang Formation (grey-green slates and quartzites), and the Silurian Phulchauki beds of dolomite.

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3.   Landslide dams in Nepal

Being a Himalayan country with the maximum number of highest peaks and deepest gorges on earth, Nepal hosts, among many others, the largest landslide in the world, called the Tsergo Ri, in the Langtang valley (Scott and Drever, 1953). The country also has many large landslide dams, some of which must have been caused by past earthquakes. A short description of some landslide dams is given below.

3.1 Coseismic landslide dams of 2015 Gorkha earthquake

The Gorkha earthquake of 25 April 2015 (**Fig. 2**) triggered off more than 2000 landslides. Most of them were shallow and did not create many landslide dams. However a number of them partially blocked major rivers and such obstructions or constrictions were washed away by the floods during the rainy season.

One of such landslide dams was formed in the Tomkhola River in the Manaslu area located to the upstream from the villages of Ghapsya and Ghap. The other landslide dam came into existence in the Marsyangdi River upstream from the village of lower Pisang. Both of these dams were identified by remote sensing using an image of Landsat 8 (NASA, 2015).

The Langtang snow and rock avalanche triggered by the mainshock of 25 April and following aftershocks of 26 April 2015 was the most devastating one. It destroyed the villages of Ghodatabela and Langtang and killed more than 100 people, including many foreigners. The avalanche temporarily blocked the Langtang Khola, which immediately started scouring the snow and debris, and created a narrow channel at the foot of the avalanche.

In the Rasuwa Gadhi area, a large rock fall – rock slide is observed on the right bank of the Bhote Koshi River, at the Nepal–China border (**Fig. 3**). The slide has partially blocked the flow and the debris is being gradually washed away by the river. A large number of shallow and long slides are seen on the right bank of the Trishuli River and in the Mailung Khola (**Fig. 4**). A few of them partially dammed the Trishuli River and were subsequently cleared off by the floodwater.

On the Arniko Highway, south of Chaku, a landslide has partially blocked the Bhote Koshi River (**Fig. 5**). Depending on the availability of the debris generated on the landslide, the material will continue to come to the river valley with a low probability of damming the river. Since the size of blocks in the debris is relatively small, complete damming seems improbable.

The Bhote Koshi River opposite the powerhouse of the Bhote Koshi Hydropower Project was also temporarily (for a few minutes) dammed by rock and debris falls (**Fig. 6**). However, at present the channel is completely free of the dammed material.

3.2 Past landslide dams in Nepal

The Tinau River has many landslide dams. One is at Butwal; other three are near Koldanda and Dumre. Also some landslide dams are seen in the Banganga River and in the Kakraha Khola of Deukhuri (Dang). But most of them are small ones.

Other landslide dams are seen in the Kali Gandaki River, near Tatopani and Lete; in the Marsyangdi River at Tal Bagar, in the Tama Koshi Valley at Lamabagar.

As mentioned by Weidinger (2011), the giant rockslide dams are located at Ringmo (Suligad Valley, Dolpa), Kalopani (Kali Gandaki Valley, Dhaulagiri Himal), Dhukur Pokhari and Latamarang (Marsyangdi Valley, Annapurna Himal).

The Budhi Gandaki valley (Manaslu Himal, Central Nepal) was dammed by two rock avalanches: one near the village of Jagat, 40 km west of Manaslu Peak, and the other one was near the village of Labubesi, 30 km NW of Gorkha. The Darbang landslide of Myagdi River valley (western tributary of the Kali Gandaki River) destroyed the village and dammed the river temporarily. The zone of failure is located at an altitude of 1100 m. The landslide of Tatopani in the lower Kali Gandaki valley was triggered off most probably by the increased pore water pressure during long periods of monsoon precipitation. The initiation of sliding with conspicuous creeping features was noticed on Sept 7, 1998 and the main failure occurred on Sept 10, 1998. The landslide continued to move for several days and temporarily blocked the Kali Gandaki River on September, 26.

Jure rockslide – rock avalanche also created a dam over the Sun Koshi River in August 2014.

The huge rockslide of Kalopani (**Fig. 7**) was reported by many, including Baade et al. (1998). It occupies several square kilometres and has completely blocked the Kali Gandaki River. Subsequently the river cut a channel across the dam.

A landslide dam (**Fig. 8**) was formed in the Kali Gandaki River, downstream from Tatopani in 1998 (Völk, 2000). It lasted for about 72 hours and was overtopped by the river without any serious consequences.

The landslide dam of Tal Bagar in the Marsyangdi River (Weidinger, 2001). It is at least 1000 years old and the river has presently filled up the dam with sediments and it is flowing through it (**Fig. 9**).
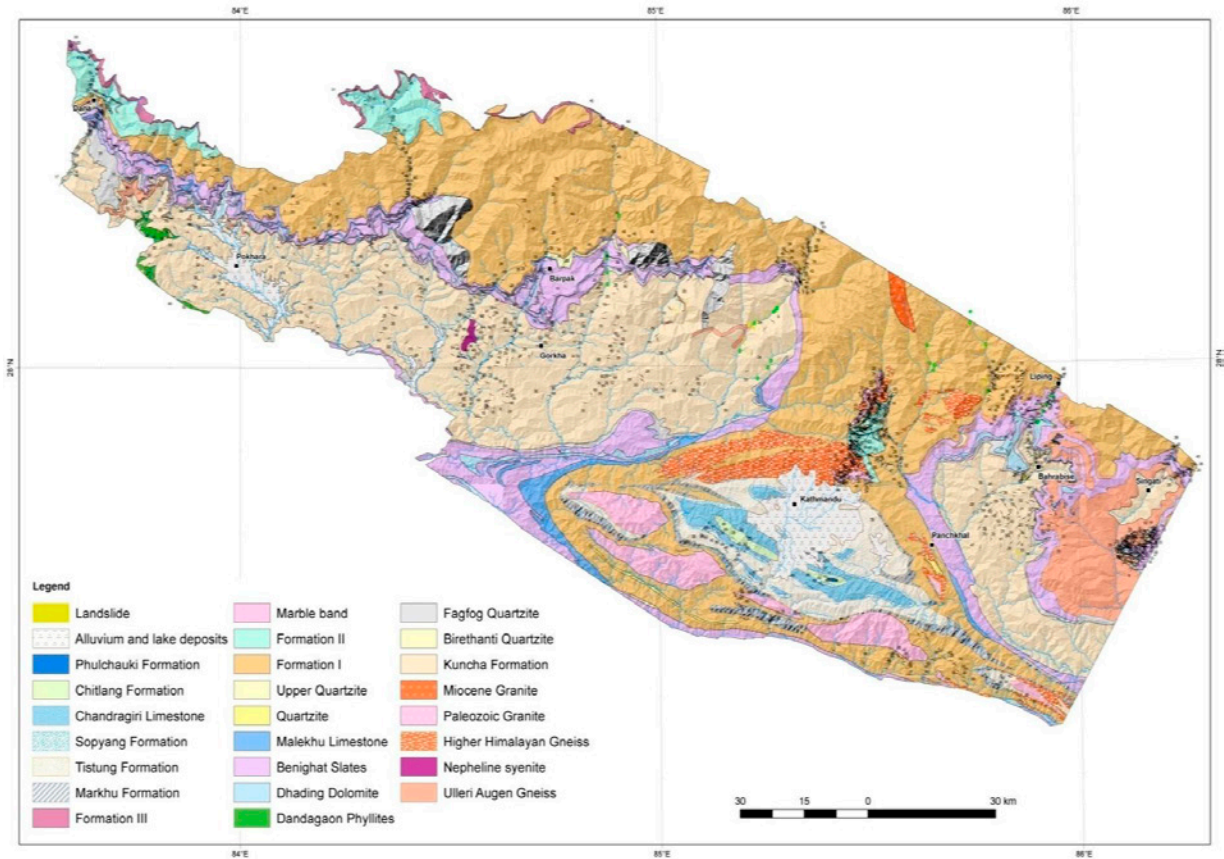
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Fig. 1. Geological map of the Kali Gandaki – Tama Koshi area in Central Nepal (Modified from Colchen et al., 1986; Dhital, 2015).
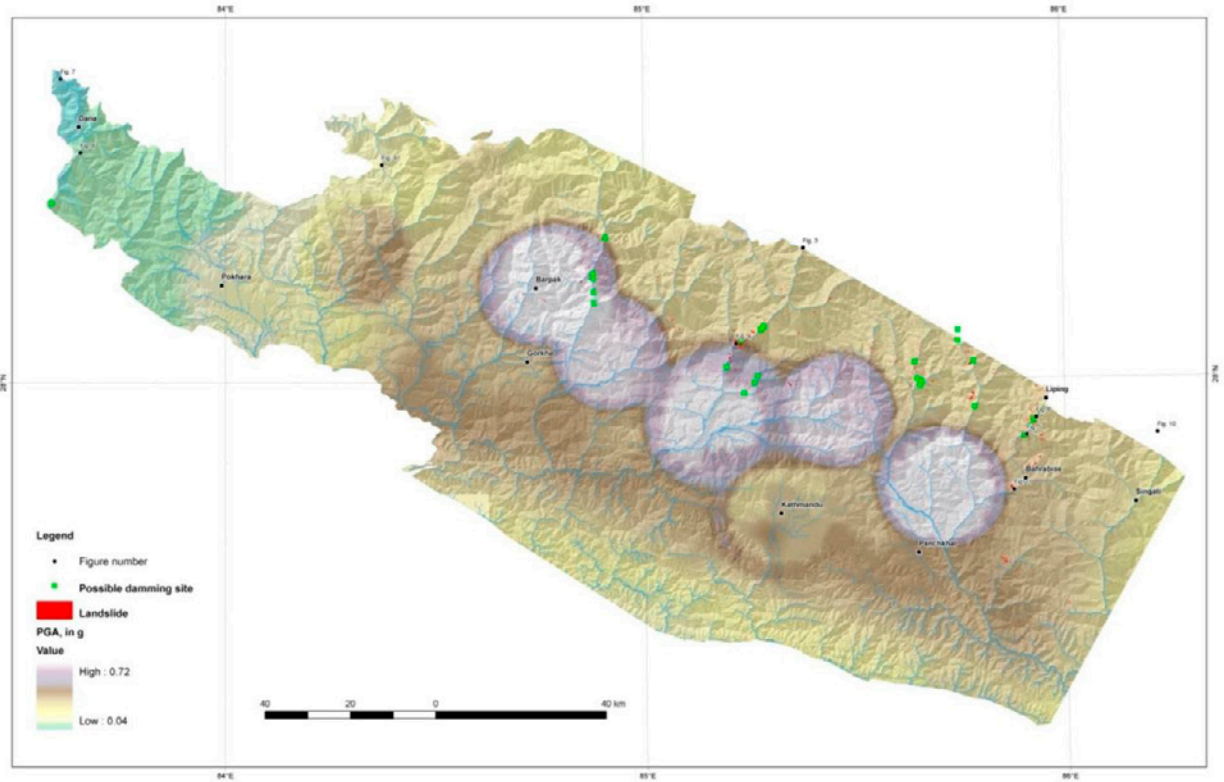

Fig. 2. Peak ground acceleration of the 25 April 2015 earthquake in the study area. Peak ground acceleration data source: USGS (2015). On the map are also shown major landslides and possible future damming sites together with locations of past landslide dams.

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Another old landslide dam is observed at Lamabagar, in the Tama Koshi River (**Fig. 10**). It is several thousand years old (Uhlir, 1998) and presently, the river is flowing through the dam.

The Jure rockslide–rock avalanche (**Fig. 11**) occurred in the morning of 14 August 2014 and it lasted for about 2 months by souring the east part of the dam. This event destroyed the headworks of the Sun Koshi Hydroelectric Project and caused damage to a few houses of Khadichaur.

4.   Stability conditions of rockslide dam

The main characteristics of past landslide dams is summarised in **Table 1**, whereas the damage caused by some large dam failures is given in **Table 2**. Most of the large dams were created by rockslides and rock avalanches. They were confined mainly in the Higher Himalayan zone where the rock is massive and has widely-spaced discontinuities.

The fluvial response of large rockslide dams was examined along the Kali Gandaki and Marsyangdi rivers by Korup et al. (2006). Both valleys have knickslopes and higher steepness indices Ks along breach channels of previously formed blockages (Hodges et al., 2004).

Weidinger (2011) worked out a relationship between volume of three rockslide dams and one rock avalanche dam scaled by height versus upstream catchment area for natural river blockages in the Kali Gandaki and Marsyangdi River valleys of Nepal (**Fig. 12**). The plot was prepared using a dimensionless blockage index (DBI=2.75) of Ermini and Casagli (2003) for worldwide data separated into stable and unstable landslide dams, by taking the empirical relationship derived by Korup et al. (2006).

5.   Parameters of landslide damming

Slowly moving landslides are not able to form landslide dam because river erodes dams gradually. The large-scale bedrock slope instability mainly causes landslide damming in rugged terrain, which could be a reason of integration impact of continuous deformation process driven by gravity force in combination with an abnormal rainstorm, snowmelt, permafrost (McColl, 2012). One of the most important triggering factors for causing large-scale catastrophic landslides that cause landslide dams is a large scale earthquake. For example, the 2008 Wenchuan earthquake in China (7.9 Magnitude) triggered 60,000 landslides (Görüm et al., 2011). Out of

60,000 landslides, a total of 256 landslide dams were identified using aerial photographs and satellite images (Xu, 2009).

Local geology and topographic factors along with stream features play prominent roles that determine if landslides occurred in an area can cause landslide damming or not. For example, areas where deep river valleys follow large fault zones seems to be the most susceptible for the formation of large landslide dams due to combination of several factors: such as presence of high steep slopes formed due to the powerful streams' incision; wide distribution of rocks weakened by faulting and fracturing typical of large fault zones and complex groundwater conditions supported by differently oriented aquifers and aquicludes. A global database analysis by Schuster (1995) indicated that the most common mechanisms triggering dam-forming landslides are excessive precipitation (58 %), and earthquakes (33 %).

6.   Factors causing landslide dam

Since landslides dam rivers, all the factors related to sliding may also become responsible for damming. The important ones are the following.

6.1 Rock type

Rock type plays a major role in landslide damming. Generally, hard and resistant rocks with wide joint spacing create large blocks that cannot be easily transported by the river (**Fig. 10**). In such circumstances, if a rock fall or slide occurs from a steep and high slope, it may dam the river (**Figs. 8, 10**, and **11**). On the other hand, a soft rock may be responsible for creating debris slides, large mud slides, debris flows, and mud flows, which can also dam a river. Sometimes alternating hard and thick bands with soft and thin bands create anisotropy in rock. In the Higher Himalayan region, quartzites and schists frequently alternate. Similarly there are alternating marble and schist bands as well as gneiss and schist bands of similar nature. In the Lesser Himalaya and the Tibetan-Tethys zone, phyllites are alternating with quartzites, sandstones are intercalated in shales and mudstones, limestones are found together with slates or shales. Hence, such conditions can favour a large rockslide or rock avalanche (**Figs. 10** and **11**).

6.2 Soil type

Though the soils found in the Lesser Himalaya, Higher Himalaya, and Tibetan-Tethys zone are generally shallow (5-10 m), sometimes very thick (exceeding 100

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Table 1. Characteristics of old landslide dams in Nepal Himalaya (Modified from Weidinger, 2006, 2011).

Location	Main causative factors	Age	Movement type	River valley	Geological settings and lithology	Angle of reach	Life span of dam
Ringmo	Folding, discontinuities, glacial erosion, stress release	30,000-40,000 (Ref: 55)	In-situ collapse	Suli Gad valley, Dolpa	Tibetan–Tethyan zone	3,5°	Still existing
Kalopani	Tectonic overthrusting, discontinuities, glacial erosion, stress release	>55.36 ± 6.95 and 55.84± 5.9 ka (Baade et al., 1998)	Translational rock sliding, rock avalanche	Kali Gandaki valley	Higher Himalayan Crystallines, augen gneiss, biotite gneiss, brecciated, cataclastic and re-cemented blocks	17°	Disappeared within late to postglacial time
Dhukur Pokhari	Discontinuities, glacial erosion, stress release	Post-glacial	Translational rock sliding, rock avalanche	Marsyangdi valley, Manang	Tibetan–Tethyan zone, limestone, schist	20°	Disappeared within a short period
Braga	Tectonic folding, glacial undercutting	Interglacial	Translational rockslide	Manang valley	Tibetan–Tethyan zone sediments	About 9°	
Latamarang	Sheeted units, discontinuities, glacial erosion, stress release	5.4 ka (Pratt-Situala et al., 2004)	Translational rock sliding, rock avalanche	Marsyangdi valley, Manang	Higher Himalayan Crystallines, and Tibetan–Tethyan zone, gneiss and quartzite	22° and 12°	More than 500 years ago (Pratt-Situala et al. 2004)
Tal	Glacial erosion, stress release	< or equal 1000 years	Rolling, bouncing	Marsyangdi valley	Higher Himalayan Crystallines, sillimanite gneiss	NA	Still stable
Lamabagar (Uhlir, 1998)	Discontinuities, glacial erosion, stress release	Three generations	Rolling, bouncing	Tama Koshi valley, Dolakha District	Higher Himalayan Crystallines, gneiss, migmatite	NA	Still stable
Gath-Chaunrikharka (Uhlir, 1998)	Discontinuities, glacial erosion, stress release	Post glacial	Rolling, bouncing	Dudh Koshi valley, Solukhumbu District	Higher Himalayan Crystallines, gneiss	NA	Felt by overtopping and erosion and outbreak after 120 years
Ghatte Khola	Stress release	Post-glacial	Rolling, bouncing	Ghatte Khola valley, Western Nepal	Lesser Himalayan Sequence, dolomite, schist	21°	Still stable
Jagat (Jacobsen, 1990)	Discontinuities, erosion, stress release, climate	Between 1962-1979	Debris flow	Budhi Gandaki valley	Lesser Himalayan Sequence, NA	NA	Outbreaks and erosion through deposit in less than 17 years
Tatopani (Völk, 2000)	Discontinuities, erosion, stress release, climate	1998	Debris flow	Kali Gandaki valley	Lesser Himalayan Sequence, phyllite, quartzite	NA	Failed due to overtopping and erosion in less than 72 hours
Labubesi (Jacobsen, 1990)	Discontinuities, erosion, stress release, climate	1968	Debris flow	Budhi Gandaki valley	NA	NA	Outbreaks and erosion through deposits, less than 17 years
Darbang	Stress release, human impact, climate	1926, 1988	Debris flow	Myagdi valley	Lesser Himalayan Sequence, schist, slate, phyllite, quartzite	23°	Failed due to overtopping and erosion in less than 6 hours

m) alluvial deposits are seen on the banks of the Kali Gandaki, Marsyangdi, and Bhote Koshi rivers. In Pokhara, such soils are more than 50 m thick. Some of the sediments could have been originated from past catastrophic debris flows, such as glacier lake outburst floods (Yamanaka et al., 1982) and landslide dams. On the other hand, the Higher Himalaya and Tibetan-Tethys zone contain a very thick till transported by numerous valley glaciers. Such loose and thick deposits are prone to debris flows and can dam the rivers on their way.

However, most of such landslide dams may not last long, because they have loose mass with relatively small size (less than 50 cm) or amount (less than 10 %).

Table 2. Table 2. Description of some past landslide dams and their damage in Nepal Himalaya (Modified from Khanal, 2011).

River/ District	Year	Description of event	Loss or damages
Budhi Gandaki/ Gorkha	1967	River was dammed for 3 days after the failure of Tarebhir near Kashigaon	There was not destruction due to outburst flood but the landslide killed 9 people
Budhi Gandaki/Gorkha	1968	Landslide occurred again in Tarebhir. Budhi Gandaki dammed near Labubesi from 10.30 AM to 2 PM. The water level dropped from normal level of 4 m on August 1 down to 0.90 m on August 2. After the breaching of landslide dam, the water level rose to 14.61 m. The peak flow was estimated to be 5210 m^3/s which was 6.93 times greater than the mean annual instantaneous flood discharge of 2380 m^3/s	One bridge and 24 houses at Arughat about 10 miles downstream of the damming site were swept away
Tinau/ Rupandehi	1970	Tinau river was blocked	92 people swept away by the flood after the breaching of dam.
Phalankhu/ Rasuwa	1971	Phalankhu Khola was dammed by landslides	5 people, one house and one water mill were swept away
Baglung	1976		7 people, 6 animals and 3 bridges swept away
Balephi/ Sindhupalchok	1982	The huge landslip of 3 sq. km blocked the river near Phalamesangu	97 people and 15 houses of Pangtang and Gunsa VDCs were swept away
Trishuli/Rasuwa	1985	From a steady flow of 350 m^3/s on 3 August 1985, the discharge dropped to 93 m3/s, 12 hours later it rose within the space of two hours to 2010 m3/s after which it dropped during 5 hours to normal flow. The ratio of peak flow was 5.74	No loss and damage took place
Tadi/ Nuwakot	1986	Slope failure of Mukut hill blocked Ghyangphedi Khola	31 people, 173 animals, 24 houses and 4 bridges were swept away
Sun Koshi/ Sindhupalchok	1987	The peak flood after breaching landslide dam was between 2150-3300 m^3/s which was as high as Glacial lake outburst flood of 1981	Two gates of Sun Koshi Hydropower dam damaged completely, water and sand entered into power house, 229 house, 98 people, 309 animals were swept away Arniko highway in many places was badly damaged
Myagdi Khola/ Myagdi	1988	After the failure of Niskot hill, Myagdi Khola dammed for 3 hours. Discharge was controlled by mobilizing local people	109 people killed, 8 injured and 94 houses were destroyed and 44 animal buried by landslides. Darbang bazaar threatened and evacuated. Discharge was controlled by blasting
Taru Khola/ Bajhang	1989	Taru Khola was dammed. The discharge was controlled by blasting with the help of Royal Nepal Army	16 people and 25 animal killed and 4 houses damaged by the landslide
Larcha	1996	Debris flow initiated after outburst of landslide dam, continuous rainfall of two weeks with low intensity initiated plane rock failure on the phyllite beds about 7 km upstream from the fan. 500 m long, maximum of 140 m wide and 12–14 m thick with average slope of 10°, maximum flow depth 7-9 m, volume about 179,500 m^3, largest boulder 10.6 x 6.8 x 6.6 m^3	Out of 22 houses, 18 houses were destroyed and 54 persons were swept away, one highway bridge
Seti River/Kaski	2012	Rock avalanche and debris flow from the Annapurna Range	It killed 72 people, damaged 7 houses, total property loss of about 1 million US dollars.
Jure/ Sindhupalchok	14 August 2014	Rockslide–Rock avalanche in the Sun Koshi valley.	It killed 137 people and destroyed 5 villages.

6.3 Orientation of discontinuities

Discontinuities in rock (such as bedding, foliation, and joints) play a major role in the creation of very large failures. In the Lesser and Higher Himalayan regions, there are predominantly three or more joint sets controlling the failure mechanism. Therefore, kinematic analysis of joints may reveal their relationship with the slope and ultimately the type of failure. Detailed analysis of discontinuities from the Bahrabise area in the Sindhupalchok District showed that the three discontinuity sets are mutually perpendicular to each other. This relationship was utilised to map the dip slope,

anti-dip slope, and dip-normal slope in the area affected by the 25 April 2015 Gorkha earthquake.

6.4 Earthquake shaking

Earthquake is one of the major causes of landslide damming. Its magnitude, intensity, peak ground acceleration, velocity, and displacement play a major role in triggering large failures that can dam the river courses. There are longitudinal or primary (p), transverse or secondary (s), and surface or long waves generated by earthquake shaking. The most devastating ones are the surface waves. The waves may be amplified or attenuat-

Fig. 3. Partially dammed Bhote Koshi River at the Rasuwa Gadhi check point in the Rasuwa District.

Fig. 4. Many rock falls, wedge slides, and plane failures in the Mailung Khola (left) and the Trishuli River (Right) south-west of Dhunche, opposite Ramche. The slides were triggered by the 25 April earthquake.

Fig. 5. Partially dammed Bhote Koshi River south of Chaku, Sindhupalchok District.

Fig. 6. Partially dammed Bhote Koshi River upstream from the Upper Bhote Koshi Powerhouse. Note extensive dust and talus on the right bank of the river.

ed depending on rock type, soil type and depth, as well as geomorphic conditions. Since the area affected by an earthquake may not have any preinstalled instruments, it is required to use some indirect methods of obtaining ground displacement. Newmark (1965) was one of the first to propose a methodology to calculate ground displacement, and his method is now widely applied to deterministically assess the earthquake hazard of an area.

6.5 Rock weathering grade and regolith

Generally, weathering makes rock weak and it also widens the discontinuities. Physical weathering loosens the mineral grains in rock, whereas chemical weathering removes unstable minerals or replaces them with those stable in given conditions. Ultimately, the rock slope becomes unstable and fails. On the other hand, if the slope is not so steep (less than 20 or 25 degrees), a soil layer (called the regolith) is developed on the rock. Based on weathering conditions, the rock can be classified into: 1) fresh, 2) slightly weathered; 2) moderately weathered; 3) highly weathered; 4) completely weathered; and finally 5) residual soil.

6.6 Position of fold or fault

The core of an anticline is weak and many slides may occur within this zone. Similarly, the core of a synclinal fold may contain much water and the confined sediments can trigger debris slides or flows. An active fault is the main source of earthquake tremor. Such faults are investigated for their type (normal, strike-slip, reverse or thrust faults), extension, width of crush zone, and their seismic activity as well as directivity. The other inactive faults may also be a threat, since they may become active in the future. The earthquake-induced failures are generally concentrated around a fault. Consequently, landslide dams are also concentrated in those areas.

6.7 Slope angle and relief

Since large rockslides in the Himalaya have occurred on steep (more than 40 degrees) and long (more than 1 km) slopes, slope angle and internal relief are one of the most important geomorphic factors. During an earthquake, rock avalanches and rock falls proliferate if a steep slope with a high internal relief is developed on widely jointed but relatively resistant rocks. On the other
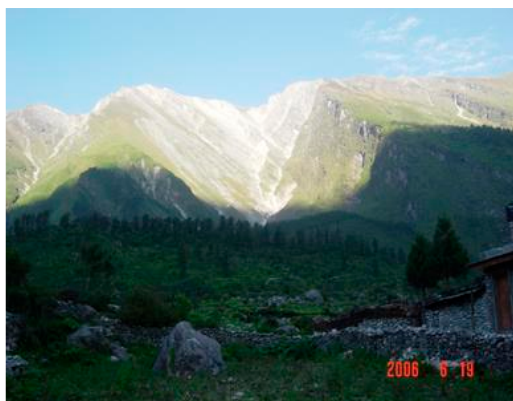
Fig. 7. Landslide of Kalopani that dammed the Kali Gandaki River several thousand years ago.

Fig. 8. Landslide dam of Tatopani in the Kali Gandaki River.

Fig. 9. Landslide dam of Tal Bagar in the Marsyangdi River.

Fig. 10. Landslide dam of Tama Koshi at Lamabagar in the Tama Koshi River.

hand, large talus cones, colluvial slopes, alluvial fans, and moraines may fail even if their slope angle is not too high (i.e., less than 25 degrees).

6.8 River morphology

River sinuosity plays a vital role in landslide damming. It is found that concave turns with steep banks suffer the most from frequent damming (**Fig. 10**). The ratio of river valley to active channel is another controlling factor of landslide dam formation and its longevity. River gradient controls landslide dam stability in many ways. Landslide dam volume and catchment area above the dam are considered the main parameters deciding the dam's stability (**Fig. 11**).

6.9 Hydro-meteorological factors

Weak rock, till, or colluvial soils may generate debris flows when there is heavy precipitation. If such large failures occur in a narrow river valley, they can create landslide dams. During monsoon, antecedent rain and the frequency of rainfall exceeding a threshold (e.g., 100 mm of precipitation in 24 hours) seem to be important factors of slope failure and landslide damming (see below). On high altitudes (exceeding 3000 m), heavy

snowfall may destabilise the moraines and other landforms on loose sediments. Similarly, when there is excessive thawing of snow during the summer time, it may also result into debris flows and landslide dams. Groundwater availability and fluctuation of perched water table also control the failure of slopes. A high pore-water pressure is developed in the joints located in steep to vertical slopes and cliffs, and such slope may fail abruptly when the strength of rock is lost (**Fig. 10**). River discharge decides the flood volume and velocity after a landslide dam fails. On the other hand, the discharge contributes to the amount of water stored behind the dam as well as the duration of overtopping. Breaching of a

Fig. 11. Landslide of Jure that dammed the Sun Koshi River on 14 August 2014.
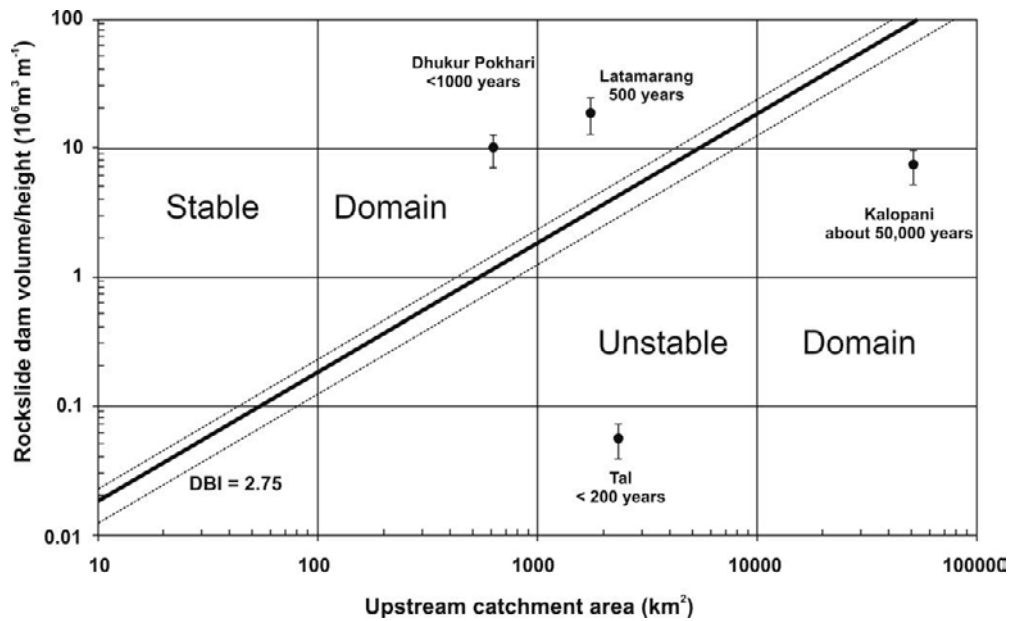
Fig. 12. Stability condition of rockslide dams based on upstream catchment area and dam volume (Modified from Weidinger, 2011).

landslide dam depends strongly on the discharge, river gradient, and the damming material.

Glacier lake outburst flood is also a major hydrological hazard. A glacier lake can form when it is dammed by a moraine, glacier ice, or both of them. Various factors, such as climate change, calving of a glacier, snow avalanche, rockslide, or rock fall can destabilize such a dam.

6.10 Anthropogenic factors

Land use practices including dry or wet cultivation and deforestation influence the adjacent slopes and contribute to their saturation and pore-water pressure development. Other activities, such as indiscriminate blasting, irrigation of unstable grounds, haphazard road construction, uncontrolled mining, and excavation of gravel and rock from slopes may lead to massive landsliding and debris flows. In some instances, such activities can accelerate the formation of landslide dams.

7. Conclusions

Though landslide dams are hard to predict, an overwhelming majority of them are associated either with earthquake or rainfall. Apart from earthquake or rainfall, other factors contributing to landslide damming include rock type and its weathering grade, discontinuity distribution and spacing, river valley and active channel widths, groundwater conditions, and soil type and depth.

The longevity of a landslide dam and volume of water stored behind it depend on the catchment area above the dam, dam width and height, geotechnical properties of damming material, and river discharge. The life span of a landslide dam varies from a few minutes to thousands of years. However, more than 85 % of them breach within a year.

The Gorkha Earthquake of 25 April 2015 and its aftershocks triggered off many shallow failures with only few landslide dams that were either very short-lived or just partially blocked the river course. The area affected by the earthquake belongs to the Lesser Himalayan Sequence, Higher Himalayan Crystallines, and the Tibetan-Tethyan zone. The severely affected area is made up of such resistant rocks as quartzites, gneisses, granites, marbles, and schists. These rocks have generally three discontinuity sets, which are almost perpendicular to each other. A detailed analysis of dip slopes, anti-dip slopes, and dip-normal slopes in the earthquake-affected area revealed that the dip-normal slopes were the most vulnerable ones. Many rockslides and rock falls began from the crest and created long runout paths.

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Development, United Nations Development Programme, Department of Soil Conservation and Watershed Management, Bhote Koshi Power Company Pvt. Ltd., Rasuwa Gadhi Hydropower Project, and Upper Trishuli 3A Project.

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