Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-461
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 22 January 2018

Brief communication: Roads and landslides in Nepal: How development affects risk

Brian G. McAdoo[1], Michelle Quak[1], Kausha Gnyawali[2], Basanta Adhikari[2], Sanjay Devkota[2], Purna Rajbhandari[3], Karen Sudmeier[4]

[1]Yale-NUS College, Singapore, 138527
[2]Department of Civil Engineering, Institute of Engineering, Tribhuvan University, Kirtipur, 44818, Nepal
[3]Independent, Kathmandu, Nepal
[4]University of Lausanne, Faculty of Geosciences and Environment, Institute of Earth Science, Lausanne, 1015, Switzerland

Correspondence to: Brian G. McAdoo (brian.mcadoo@yale-nus.edu.sg)

Abstract. The number of deaths from landslides in Nepal has been increasing dramatically due to a complex combination of earthquakes, climate change, and an explosion of road construction. We compare the distribution of landslides in Sindhupalchok district before the 2015 Gorkha Earthquake with those generated by the earthquake to demonstrate that landslides are more than twice as likely to occur near a road than a random distribution. Based on this finding, geoscientists, planners and policymakers must consider how development needs overlap with physical (and ecological), socio-political and economic factors to generate risk in exposed communities.

1. Introduction

On 29 and 30 July 2015, during the first monsoon season following the Mw=7.8 Gorkha earthquake, landslides triggered by a dramatic cloudburst killed 29 people in Nepal's Western Region (**BBC, 2015**). These deadly landslides and many others like them are not solely the result of intensified rainfall associated with climate change (**Bharti et al., 2016)**, but a complex intersection of socio-economic factors with a highly-altered physical landscape where non-engineered roads regularly fail during the annual monsoon season. This problem will become more acute as China's "One Belt, One Road" initiative seeks to link an expanded trade network to markets in Nepal, India and beyond via a series of trans-Himalayan corridors with very complex geomorphic processes (**Bhushal, 2017**). This expanded transportation network will further alter the surrounding landscapes as villages seek to link to these lines with roads constructed and maintained with severely limited resources.

Many villages in the Middle Hills region of rural Nepal are connected by simple footpaths. As the nation continues its development trajectory, communities hire heavy machinery (funded in large part by remittances) to expand these pathways into vehicular roads for better access markets, educational opportunities, and healthcare. The resulting non-engineered roads often create landslides by undercutting slopes, providing pathways for water to seep into potential slide planes, and producing debris that is easily mobilised during heavy rainfall (e.g. **Sidle et al., 2006**). Disruption of transportation networks that bring much needed goods and serves to and from rural communities, damage to agricultural lands in regions where subsistence farming is the norm, and the scores of deaths that occur every year all act to counter sought after developmental gains.

To better understand the link between geologic hazards and development, we examine the relationship between roads and landslides Sindhupalchok district of Central Nepal (**Fig. 1**). Sindhupalchok was heavily impacted by the 2015 Gorkha earthquake- over 95% of the houses were severely damaged and over a third of the deaths occurred here (**ReliefWeb, 2017**). The earthquake generated over 7,000 co-seismic landslides in this district (**Gnyawali and**

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-461
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 22 January 2018

Adhikari, 2017), many of which intersect rural roads. Furthermore, infrastructure along one of the main trunk roads that links China and Kathmandu was severely damaged, resulting in the closure of the border crossing which has not been reopened as of this writing. By comparing the spatial distribution of landslides generated by the earthquake with those from the previous monsoon season with the emergent roads network, we can better understand the role of roads in generating landslides.

The distribution of more than 19,000 landslides generated by the Gorkha earthquake is similar to that generated by other earthquakes- the primary controls are related to rupture location and direction and peak ground acceleration, as well as the physical characteristics of the topography including slope, aspect and curvature (**Gnyawali and Adhikari, 2017**). In Sindhupalchok, the 7,091 landslides are correlated with soil type, where most landslides occur in the better developed humic cambisols than in the eutric regosols that occur in higher, more arid zones (**Dijkshoorn and Huting, 2009**; **Fig. 1a**). Because the humic cambisols better support agriculture, most of the roads are also located in this zone.

2. Methods

Using the distribution of the earthquake-generated landslide areas, we ran a Monte Carlo simulation that distributed 7,091 landslides randomly over the cambisol zone to determine if there is a correlation with the roads. Using the existing road network (**OpenStreetMap Contributors, 2017**), we created buffers at 50 m intervals normal to the road, and counted the number of landslides that intersect the buffer at a given distance (**Fig. 1b**). If more earthquake-generated landslides occur closer to the roads than the random distribution, then it would suggest that the existence of the roads predisposed the landscape to failure during strong shaking. If, however, the coseismic landslides match the random, then the presence of roads has little effect on earthquake-generated landslide risk.

In addition to checking the earthquake-generated landslides with a random distribution, we also did the same for recent landslides that were present before 2015, presumably generated by monsoon rainfall. We have mapped 139 landslides in the cambisol soil type in Sindhupalchok district with a not too dissimilar area distribution as the co-seismic landslides. Using the same Monte Carlo simulation, we used the area histogram of these slides to create a random distribution over the landscape and counted the number of landslides at the various distances from the roads.

The randomly generated slides from both the co-seismic and rainfall triggered landslides together along with the actual landslides generated by the earthquake, showing that 20-25% occur within 100 m of a road **(Fig. 2).** The landslides that predate the earthquake, however, are more than twice as likely to have occurred near a road, where 47% of slides occur within 100 m of a road. The percentages of both classes of landslides increases predictably as the buffer distance from the road increases.

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-461
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 22 January 2018

Natural Hazards and Earth System Sciences
Open Access
Discussions

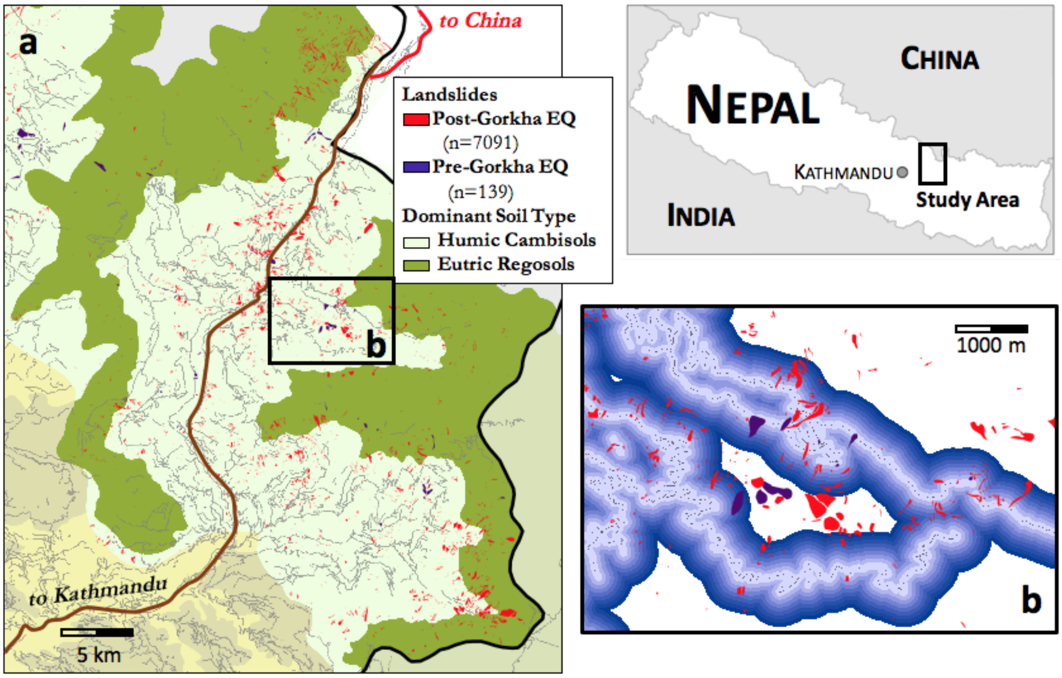

Figure 1. Roads and landslides in Sindhupalchok district, Nepal. (a) The Arniko Highway that runs between Kathmandu and Kodari at the Chinese border was heavily impacted by the 2015 Gorkha earthquake. The red polygons mark the location of landslides generated during the earthquake, and the blue polygons were the landslides that occurred during the monsoon season before the earthquake (2014). Most landslides correspond with the humic cambisol soil type as mapped by **Dijkshoorn and Huting (2009)**. (b) Along all the roads in the study area, we placed buffers at 50 m intervals to determine the number of landslides within a given distance from the road.

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-461
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 22 January 2018

Natural Hazards and Earth System Sciences
Discussions

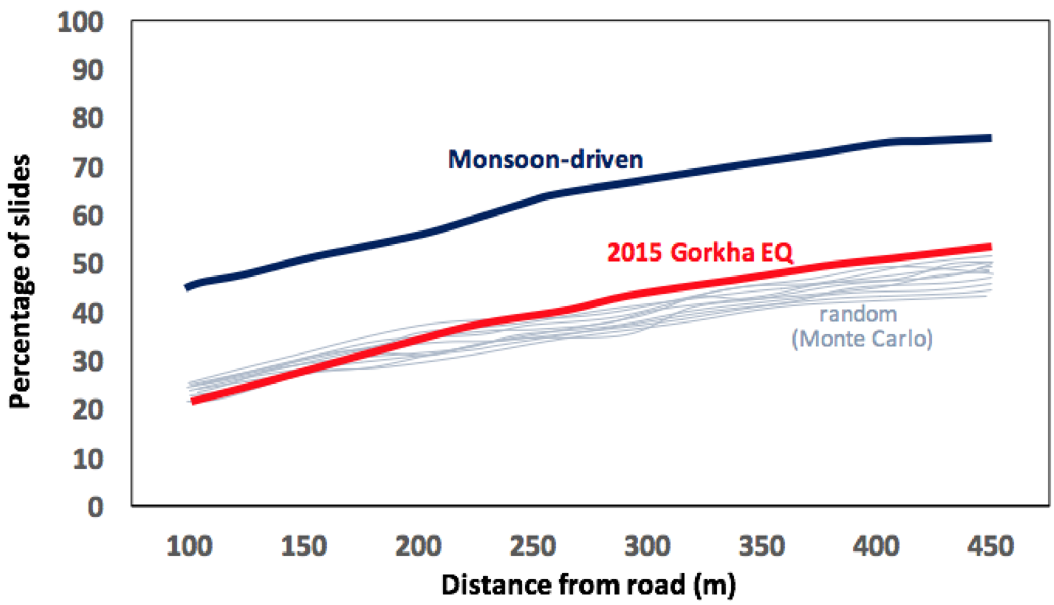

Figure 2. Roads and Landslides, Sindhupalchok District, Nepal. The grey lines represent the number of randomly-located landslides that are a given distance from a road, whereas the red line represents the distances earthquake-generated landslides (n=7,091) are from road, and the blue line the distance of monsoon-generated landslides (n=139) are from roads. These data demonstrate that roads are a significant generator of landslides.

3. Discussion

In the late 1970's, the fraction of landslides associated with roads in Nepal was 5% of the total number of slides, and at that time the land surface covered by roads was, "infinitesimally small" (**Laban, 1979**). As road networks continued to increase, it was predicted that the number of associated landslides would increase drastically, especially if more careful construction methods were not implemented, hindering the nation's development trajectory, jeopardising the well-being of its inhabitants. The data presented here confirm that roads significantly increase the likelihood of landsliding, and if the quality of road construction does not improve, losses will increase significantly as development continues.

The evolution of Nepal's road network and subsequent increase in landslide risk has occurred in a complex socio-ecological and physical environment marked by a rapidly changing climate that is producing more intense rainfall events during the monsoon (**Bharti et al., 2016**) and geopolitical upheaval that increased vulnerability during the 1996-2006 Maoist insurgency. The political climate leading up to the late 1970's was becoming tense due to rural Nepal's, "semi-colonial experience", that supported, "forced stagnation in production and productivity", eventually precipitating the 10-year long uprising (**Basnett, 2009**). The instability associated with the rebellion resulted in a stagnation of foreign direct investment (FDI) which averaged $7.5 M USD per year during the revolt to $53 M per year between 2007 and 2016 (2016 dollars; World Bank, 2017). This increase in FDI helped fund a 55% increase in the length of the road network from 19,150 km to 27,120 km (**MoF, 2016**). While these government-funded roads are designed by engineers, the concern lies with the informal earthen and gravel roads that seek to tie into these-prior to the insurgency, these rural roads represented a third of the total, yet now with the much expanded network, represent over half the roads in Nepal (**MoF, 2016**).

The One Belt, One Road initiative fits well with the Nepali government's long-term development strategy to promote road development (**Murton, 2016, The Economist, 2017**). With the onus of construction and maintenance of rural roads in the hands of local communities and politicians, scarce funds needed for road maintenance compete with the need for investment in other sectors. **Leibundgut et al. (2016)** found that the economic impact of rural roads around Phewa Lake, Kaski district of western Nepal amounted to $117,287 USD/year in maintenance costs, forecasted to rise to $192,000 USD/year by 2030 with the current rate of road construction.

While the number of deaths from landslides that occurred during the insurgency dropped from 146 deaths/year to 130 deaths/year in the years following, there are on average 9.4 additional deaths occurring each year despite the number of landslides dropping at a rate of 9.6 fewer landslides each year (**DesInventar, 2017**). This suggests that while the overall vulnerability has dropped, the population is still at risk as road networks continue to expand into fragile, highly vulnerable territory where fewer landslides are killing more people. As more communities attempt to improve their standards of living by tying into these transportation networks, and without proper funds dedicated to maintenance, the financial and human losses will continue to mount.

4. Conclusions

Landslides in the Anthropocene are no longer simply a function of geomorphology and climate, and in Nepal, roads are changing the equation. Better engineered roads will lead to more sustainable economic development, but these roads come with a price. As FDI aids construction, maintenance costs fall on impoverished communities who must decide between access and basic services. Green solutions such as plantings on metastable hillslopes are more economically sustainable and can be implemented by community members with minimal training. There is little that can be done to control the climate, but economically feasible and environmentally sound interventions will reduce losses in resources and lives.

Acknowledgements
The authors would like to thank Yale-NUS College for supporting field research in Nepal. Special thanks go to our colleagues A. Pang, S. Chee, A. Dominguez, and the students from the Yale-NUS College Learning Across Boundaries Nepal programme.

References

Basnett, Y., From Politicization of Grievances to Political Violence: An analysis of the Maoist Movement in Nepal, Development Studies Institute, Working Paper Series No. 07-79 (2009).

Bharti, V., Singh, C., Ettema, J.,& Turkington, T. a. R. Spatiotemporal characteristics of extreme rainfall events over the Northwest Himalaya using satellite data. International Journal of Climatology, 36(12), 3949–3962. https://doi.org/10.1002/joc.4605 (2016).

Bhushal., R., "One Belt, One Road Fuels Nepal's Dreams", The Wire (India), https://thewire.in/156554/nepal-china-obor-transport-infrastructure (2017).

British Broadcasting Corporation, Landslides triggered by rain kill at least 29, http://www.bbc.com/news/world-asia-33714147, 2015.

Desinventar Disaster information management system, Profile - Nepal http://www.desinventar.net/DesInventar/profiletab.jsp?countrycode=npl

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-461
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 22 January 2018

Natural Hazards and Earth System Sciences
Open Access
Discussions

Accessed December 13, 2016

Dijkshoorn, J.A. and Huting, J.R.M., Soil and terrain database for Nepal. Report 2009/01, ISRIC – World Soil Information, Wageningen, The Netherlands, http://www.isric.org/isric/webdocs/docs/ISRIC_Report_2009_01.pdf, 2009.

Economist, India faces growing competition with China in its own backyard, 19 December 2017.

Gnyawali, K. R. and Adhikari, B., Spatial Relations of the Earthquake Induced Landslides Triggered by 2015 Gorkha Earthquake Mw = 7.8, in Advancing Culture of Living with Landslides, M. Mikos et al. (eds), 2017.

Laban, P., Landslide Occurrence in Nepal, Food and Agriculture Organisation, Editor. 1979, Food and Agriculture Organisation, Government of Nepal, Ministry of Forest, Soil and Water Conservation, UNDP: Kathmandu. p. 30 p.(1979).

Leibundgut, G. Sudmeier-Rieux, K., Devkota, S. Jaboyedoff, M. Derron, Marc-Henri, Penna, I., and L. Nguyen (1979).Rural earthen roads impact assessment in Phewa watershed, Western region, Nepal. *Geoenvironmental Disasters* (2016) 3:13. DOI 10.1186/s40677-016-0047-8

MoF [Ministry of Finance, Government of Nepal], Economic Surveys 2001-2015, http://www.mof.gov.np/en/archive-documents/economic-survey-21.html, accessed on 29 November 2016.

Murton, G. (2016) A Himalayan Border Trilogy: The Political Economies of Transport Infrastructure and Disaster Relief between China and Nepal. *Cross-Currents: East Asian History and Culture Review E-Journal No.18* (March 2016).

Open Street Map Contributors, https://planet.openstreetmap.org/, accessed between April and December, 2017.

Petley, D., Hearn, G.J., Hart, A., Rosser, N., Dunning, S., Oven, K., & Mitchell, W. Trends in landslide occurrence in Nepal. *Nat Hazards*, 43: p. 23–44. (2007)

ReliefWeb, Nepal Earthquake: District Profile- Sidhupalchok 08.05.2015, (https://reliefweb.int/report/nepal/nepal-earthquake-district-profile-sindhupalchok-08052015), accessed on 12 December 2017.

Sidle, R.C. & Ochiai, H. *Landslides: Processes, Prediction, and Land Use*. Water Resources Monograph Series, volume 18. Washington, D.C.: American Geophysical Union.(2006).

The Economist. December 23, 2017. The two sides of the mountain. https://www.economist.com/news/asia/21732851-maldives-nepal-and-sri-lanka-are-no-longer-meek-they-used-be-india-faces-growing

World Bank Open Data, https://data.worldbank.org/, accessed on 17 July 2017.