*Geo-Resilience 2023 Conference, Cardiff, Wales*
*D.G. Toll & M.G. Winter (Eds)*
*British Geotechnical Association, London. 2024*
*https://doi.org/10.53243/Geo-Resilience-2023-1-9*

# The Resilience of Critical Infrastructure in Nepal to Earthquake and Monsoon Induced Landslides

Michael R Z WHITWORTH[1], Joshua JONES[1], Sarah J BOULTON[2], Martin STOKES[2], Georgina BENNETT[3]

[1]AECOM Ground Engineering, Plymouth, UK
[2] University of Plymouth, School of Geography, Earth and Environmental Sciences, Plymouth, UK
[3] College of Life and Environmental Sciences, University of Exeter, Exeter, UK

Corresponding author: Michael R Z Whitworth (michael.whitworth@aecom.com)

**Abstract**

Nepal is impacted by a range of geological and meteorological hazards and is ranked in the top 10 of countries affected by climate change. Landslides pose a particularly significant hazard, with >24,000 landslides triggered by the 2015 Gorkha earthquake and hundreds of landslides triggered annually by monsoonal rainfall. These events impact various critical infrastructure including transportation routes and hydropower projects.

This paper presents an evaluation of the resilience of critical infrastructure in Nepal to the impact of earthquake and monsoon induced landslides. The research focus is along the Araniko Highway, 80km NE of Kathmandu, which is a critical transportation and economic corridor between Nepal and China and the location of existing and ongoing hydropower development along the Bhotse Khosi River.

As well as being critical in terms of its economic importance, the Araniko Highway is pervasively impacted by landslides. For example, in 2014, landslides caused significant damage to the road, electricity distribution network, and hydropower projects, including the Jure landslide that killed over 156 people and dammed the river. In 2015 the Gorkha earthquake tiggered hundreds of landslides, closing the highway for 5 months. In 2016 a Glacial Lake Outburst Flood (GLOF) permanently closed the highway and caused significant damage to hydropower projects. Despite this, there remains only a limited understanding of how geological and geomorphological factors influence these hazards, with little attempt made to date to mitigate the impacts of these hazards and improve resilience to future events.

As such, this paper presents field survey and remote sensing observations made along the Araniko Highway between 2016 and 2022. These observations are used to perform high-level geo-spatial assessments of specific landslides that have impacted critical infrastructure, which are used to evaluate what geological and geomorphological factors influenced these events, and how they could be mitigated to improve future resilience.

Keywords: Critical Infrastructure, Resilience, landslides, Nepal, Geological Hazards Asset Resilience

## 1. Introduction

Nepal is impacted by a range of geological and meteorological hazards and is one of the country's most susceptible to the impact of climate change (Paudel et al., 2003, JICA, 2012). Landslides pose a particularly significant hazard, with >24,000 landslides triggered by the 2015 Gorkha earthquake (Zekkos et al 2017, Jones et al 2021a) and hundreds of landslides triggered annually by monsoonal rainfall (Jones et al 2021b). An Assessment of disasters that impact Nepal indicates that there is an increasing trend of the impact of geological and meteorological hazards (Government of Nepal, Ministry of Home Affairs, 2016). These events impact various critical infrastructure including transportation routes and hydropower projects and previous assessment of the resilience of this critical infrastructure is extremely low (Whitworth et al 2020).

This paper presents an evaluation of the resilience of critical infrastructure in Nepal to the impact of earthquake and monsoon induced landslides, utilising the Ariniko Highway (Figure 1) as a case study. The Ariniko Highway is a key economic corridor between Nepal and China, with 90% of the trade between the countries occurring along this route. In addition, Billions of dollars' worth of investment is being invested along the adjacent Bhotse Khosi River. However, the river and road system are severely impacted by a range of geological and meteorological hazards. In 2014, landslides caused significant damage to the road, electricity distribution network, and hydropower projects, including the Jure landslide that killed over 156 people and dammed the river. In 2015 the Gorkha earthquake tiggered hundreds of landslides, closing the highway for 5 months. In 2016 a Glacial Lake

Outburst Flood (GLOF) (Cook et al 2018) permanently closed the highway and caused significant damage to hydropower projects. Despite this, there remains only a limited understanding of how geological and geomorphological factors influence these hazards, with little attempt made to date to mitigate the impacts of these hazards and improve resilience to future events.

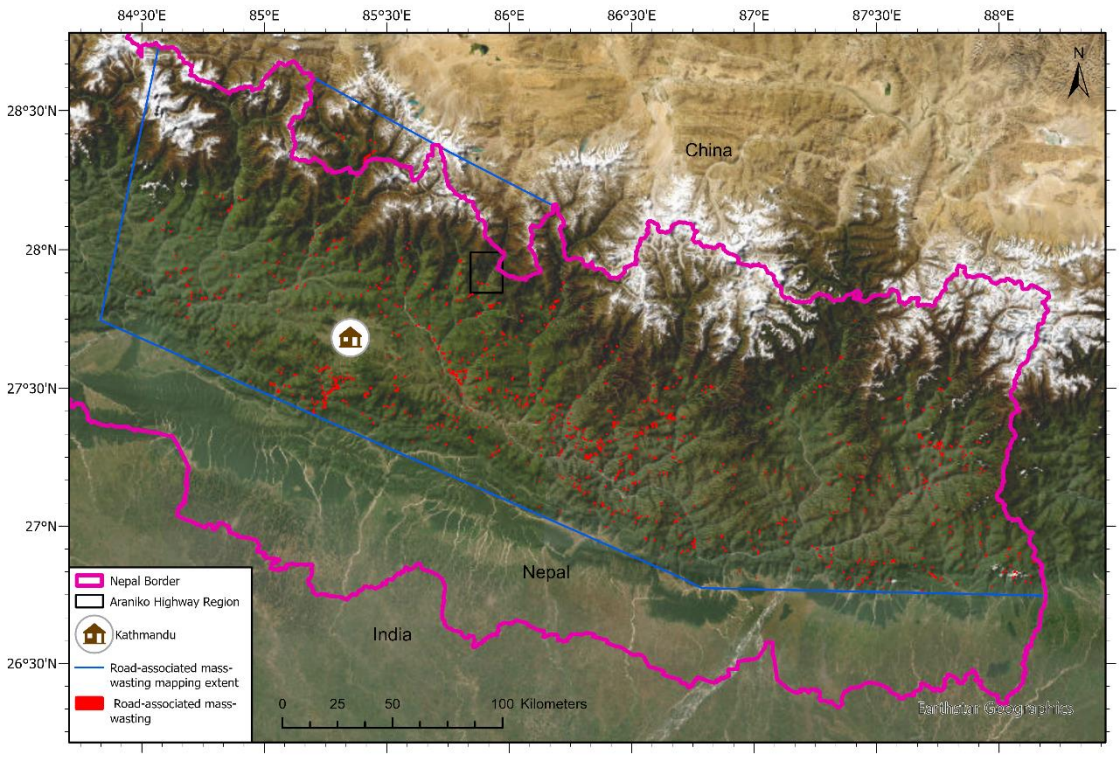


**Figure 1**: Location Plan of Nepal and the Study Area of the Ariniko Highway. Figure also highlights mapped landslide events associated with roads.

This paper presents field survey and remote sensing observations made along the Araniko Highway between 2016 and 2022. These observations are used to perform high-level geo-spatial assessments of specific landslides that have impacted critical infrastructure, which are used to evaluate what geological and geomorphological factors influenced these events, and how they could be mitigated to improve future resilience.

## 2. Methodology

### 2.1 Field Mapping

In the Araniko Region, 177 landslides were mapped within the field during October 2019. These landslides were mapped using the following approach. First, the locations of an observed landslide would be recorded using a GARMIN 78 series handheld GPS unit. For landslides that were physically accessible (i.e., they intersected a trekking path or road) the GPS coordinates were recorded as being 'on the landslide'. For landslides that were being viewed on the opposite side of a valley the coordinates were recorded as being 'opposite the landslide' and the compass direction between the GPS location and the landslide was recorded. In addition, where possible, for each landslide descriptions were taken regarding landslide size, morphological characteristics (source/runout/deposition zone location, size, and shape), level of vegetation, bedrock and soil types, and general surrounding landscape geomorphology (e.g., whether there were rivers, terraces, relict channels, the state of the terrain etc.).

Of the 177 landslides mapped in the field, 161 (91%) were assessed as likely being coseismic rockfalls and debris flows triggered by the 2015 Gorkha earthquake, and the remaining 16 (9%) as being monsoon-triggered slumps/slides and relict alluvial fans. Distinguishing between coseismic and monsoon-triggered landslides was predominantly based on whether or not a landslide initiated at the hillslope toe or ridge, under the assumption that coseismic landslides occur at ridgelines, and rainfall-triggered nearer the slope toe (Densmore & Hovius

2000). Where possible, local knowledge was also obtained on specific landslides by speaking with members of nearby populations to ascertain whether they could provide further insight into when and how a given landslide occurred.

Figure 2 is a photomontage illustrating a range of both earthquake and monsoon trigger landslides and their impact.

**Figure 2**: Photo montage of the impact of both earthquake and monsoon landslides to critical infrastructure along the Ariniko highway.

### 2.1 Remote Sensing

Once mapping had been completed in the field, the identified landslides were corroborated using 0.5m spatial resolution Google Earth Pro/CNES/Airbus imagery from 2018 - 2020. This was done because field mapping has inherent sampling bias introduced by the fact that the topography results in only being able to map landslides that are visible from the ground. The field observations and remote imagery were then used in tandem to delineate final polygons of each mapped landslide. The available satellite imagery was also used to remotely map landslides that were unreachable in the field, to ensure that the landslide inventory for the region was

sufficiently complete. As such, the final inventory should be considered a combined field-remote sensing inventory. The remote imagery added a further 304 assumed coseismic landslides to the inventory.

To assess how road building affects gravity driven landslide/mass-wasting processes through time, 15-30m spatial resolution Landsat 4/5/8 imagery was obtained between 1988 and 2018 in the mapping region shown in Figure 3. For each year, imagery was obtained before and after each monsoon season, i.e., obtained for the period October – March. The imagery was then processed to in ArcGIS pro to a false colour RGB image that highlights the reflectivity of bare earth relative to vegetation using the near infrared band. The imagery was then compared before and after each year's monsoon season to visually identify landslides or general mass-wasting occurrences that had occurred simultaneously with the construction of a new road (e.g., Figure 3).

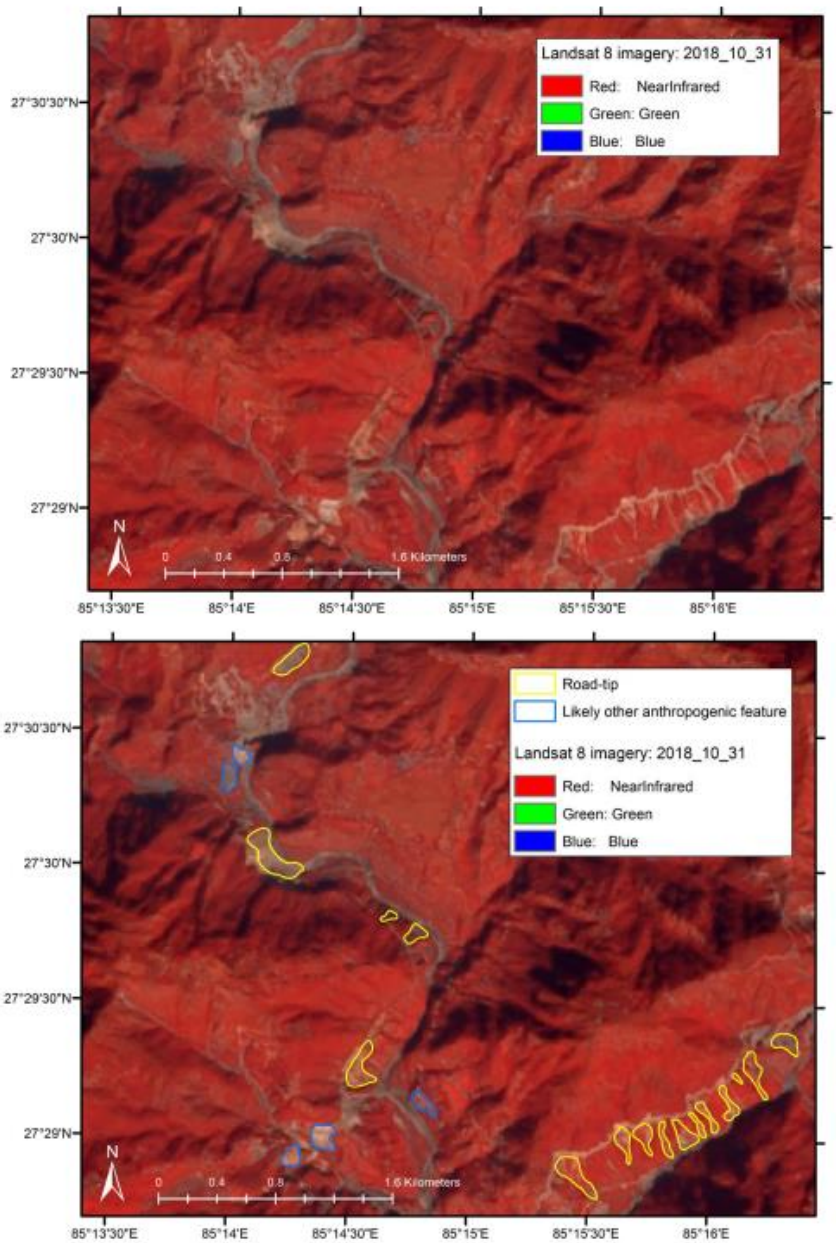


**Figure 3**: Example panels showing landslide/mass-wasting that had occurred beneath a new road in imagery from false RGB Landsat imagery from 2018.

## 3. Results and Discussion

The final inventory showing both the field and remote sensing mapped landslides is shown in Figure 4 alongside the main towns, transportation routes and hydro-dam infrastructure in the region. With almost 500 mapped landslides identified in total. From Figure 2 and Figure 4 it can be seen that these landslides have a significant impact on not only residential developments, but also on critical infrastructure including the main transportation route between Nepal and China, the Ariniko highway and existing hydro-power developments.

Initial field observations were undertaken in 2019, with subsequent field visits undertaken in 2022 to evaluate the resilience and recovery of the infrastructure to these landslide events. The subsequent field visits identified that the landscape appeared to be recovering from the earthquake induced landslides, with little evidence of continued reactivation, confirming the findings of Jones et al 2021b. However, there was continued rainfall induced landslides events and although the border and highway had reopened to a low volume of traffic and along the corridor there appeared an increase in economic activity, the critical infrastructure continues to be impacted by landslides, with previous mitigation measures, having minimal impact (Figure 5).

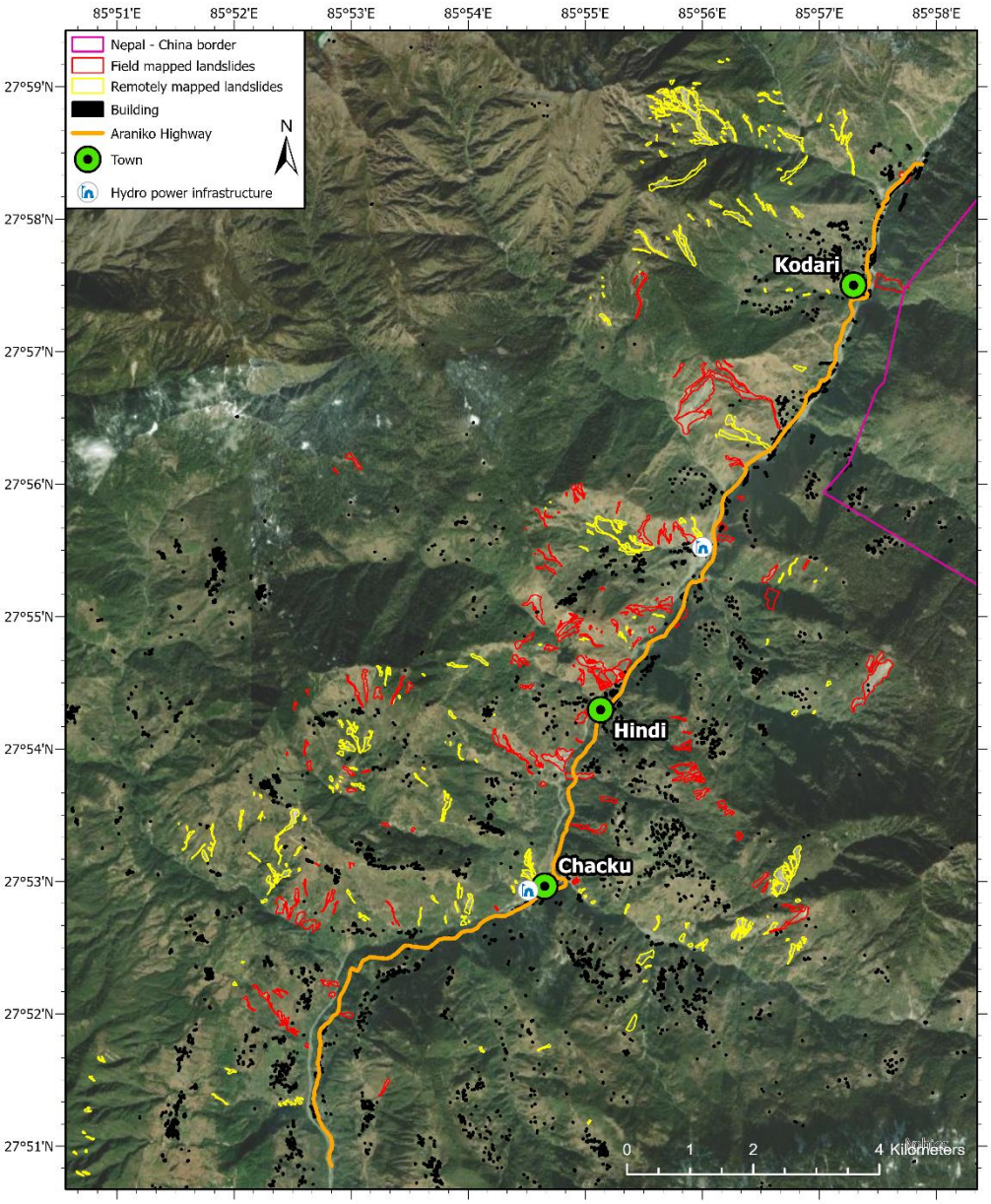


**Figure 4:** Map showing the location of monsoon and earthquake inducted landslides identified from field reconnaissance and remote sensing in relation to critical infrastructure

**Figure 5**: Left – photo of remediation/mitigation works of major landslide along the Ariniko highway in 2019. Right – similar viewpoint of same landslide taken in 2022 showing reactivation of landslide and ongoing landslide activity.

Through site reconnaissance it was identified that human influence was also a contributing factor to landslide occurrence, through a variety of factors including oversteepening of slopes and side tipping. Froude and Petley et al 2018 investigated global landslide occurrence from 2004 and 2016 and identified that landslide occurrence triggered by human activity is increasing. To investigate anthropogenic influence on landslides an assessment of landslides influenced by road building activities was undertaken within GIS for the whole of Nepal. These road-related mass-wasting features were delineated as polygons for each year. The total area of these polygons was then summed using ArcGIS spatial analyst tools and plotted through time to provide a preliminary assessment of how road-associated mass-wasting was changing through time (Figure 5). This shows a general increasing trend in road-associated mass-wasting, with a near-exponential increases since 2015.

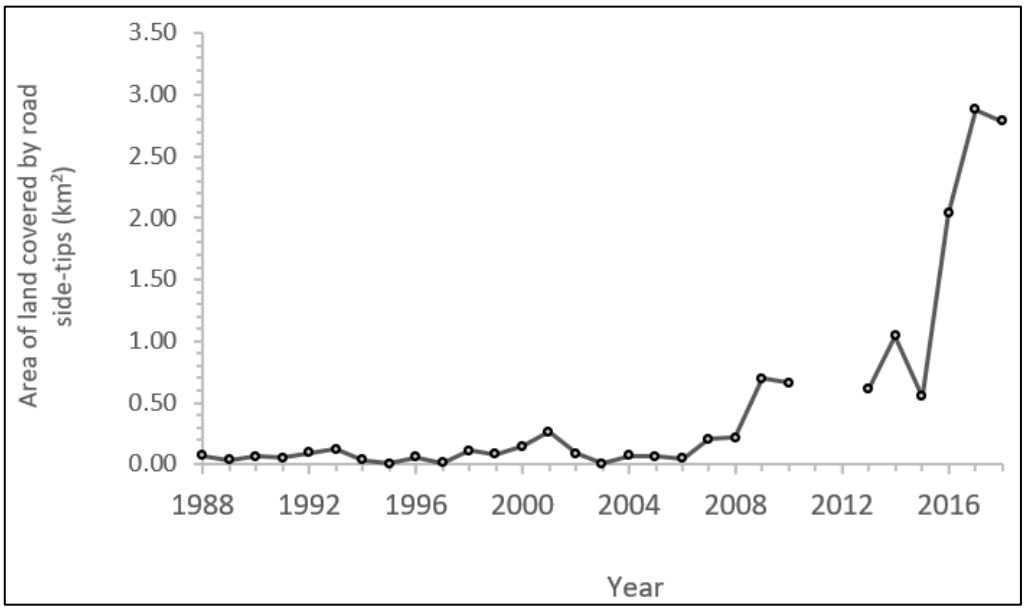


**Figure 5**: Remote Sensing analysis of the anthropogenic influence on landslide occurrence through time within Nepal.

**4. Conclusions**

Based on field reconnaissance undertaken between the period 2017 and 2022, it has been identified that Nepal is significantly impacted by monsoon and earthquake induced landslides. Using a case study of the Ariniko Highway and the adjacent Bhotse Khosi river catchment, as well as the loss of life, critical infrastructure such as

transport and hydropower developments and severely impacted by a range of geological and meteorological hazards including landslides. Both monsoon and earthquake induced landslides have impacted residential developments, transport infrastructure as well as remote trails, impacted hydropower development and the electricity transmission network. These events have had a significant impact on the economic development of both the region and Nepal including the closure of the main China – Nepal Land boarder.

Through field observations, limited mitigation to geological and meteorological hazards appears to have been considered, with little to no change in the resilience of the critical infrastructure to geological and meteorological hazards. Furthermore, an assessment of mass wasting due to road building indicates that the anthropogenic influence on landslide development has increased significantly over the last 30 years contributing to the impact of landslides on critical infrastructure.

To improve resilience to meteorological and geological hazards, detailed assessments need to be undertaken to mitigate the impact of earthquake and monsoon landslides on critical infrastructure within Nepal, including the impact of climate Change. Further work is required to understand the anthropogenic influence on landslide occurrence and potential impact

**References**

Cook, K.L., Andermann, C., Gimbert, F., Adhikari, B.R. and Hovius, N., 2018. Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya. *Science*, *362*(6410), pp.53-57.

Froude, M.J. and Petley, D.N., 2018. Global fatal landslide occurrence from 2004 to 2016. *Natural Hazards and Earth System Sciences*, *18*(8), pp.2161-2181.

Japan International Cooperation Agency (JICA), Nippon Koei Co., Ltd. and Eight-Japan Engineering consultants Inc., 2012. Data collection survey on traffic improvement in Kathmandu valley: final report. Available at: http://open_jicareport.jica.go.jp/737/737/737_116_12082459.html

Jones, J.N., Stokes, M., Boulton, S.J., Bennett, G.L. and Whitworth, M.R.Z., 2020. Coseismic and monsoon-triggered landslide impacts on remote trekking infrastructure, Langtang Valley, Nepal. *Quarterly Journal of Engineering Geology and Hydrogeology*, *53*(2), pp.159-166.

J. N. Jones., S. J. Boulton., G. L. Bennett., M. Stokes., & M. R. Z. Whitworth., 2021, 30-year record of Himalaya mass-wasting reveals landscape perturbations by extreme events, *Nature Communications, 12, 6701 (2021), https://doi.org/10.1038/s41467-021-26964-8*

J. N. Jones., S. J. Boulton., G. L. Bennett., M. Stokes., & M. R. Z. Whitworth., 2021, Temporal variations in landslide distributions following extreme events: implications for landslide susceptibility modelling, *Journal of Geophysical Research Earth Surface, vol 126, issue 12, doi.org/10.1029/2021JF006067.*

UNISDR, 2015. Sendai Framework for Disaster Risk Reduction 2015-2030. United Nation Office for Disaster Risk Reduction

Ministry of Home and Affairs, 2015. Earthquake in Gorkha. Kathmandu, Nepal: 29-31.

Paudel, P. P., Omura H., Kubota T. and Morita, K., 2003. Landslide damage and disaster management system in Nepal. In Disaster Prevention and Management, 12 (5): 413 -419.

Whitworth, M.R., Moore, A., Francis, M., Hubbard, S. and Manandhar, S., 2020a. Building a More Resilient Nepal-The Utilisation of the Resilience Scorecard for Kathmandu, Nepal Following the Gorkha Earthquake of 2015. *Lowland Technology International*, *21*(4, March), pp.229-236.

Whitworth, M.R.Z., Boulton, S. and Jones, J., 2020b. Implementing the Sendai Framework in developing countries using remote sensing techniques for the evaluation of natural hazards.

Zekkos, D., Clark, M., Whitworth, M., Greenwood, W., West, A.J., Roback, K., Li, G., Chamlagain, D., Manousakis, J., Quackenbush, P. and Medwedeff, W., 2017. Observations of landslides caused by the April 2015 Gorkha, Nepal, earthquake based on land, UAV, and satellite reconnaissance. *Earthquake Spectra*, *33*(1_suppl), pp.95-114.