Landslides caused by the 14 November 2016 Kaikoura earthquake, South Island, New Zealand

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ABSTRACT

At 12.03 am local time on 14th November 2016 (UTC: 11.03 am 13th November 2016) a shallow, magnitude 7.8 earthquake struck near Waiau in North Canterbury, NZ. Strong ground shaking affected the North Canterbury and Marlborough regions of the South Island, causing widespread damage to buildings and infrastructure across these sparsely populated areas. Mid-rise (8-15 story) buildings in Wellington were also damaged. The most visible consequence of the strong ground shaking was widespread landslides. The area affected by landslides is sparsely populated, only a few dwellings were impacted and there were no recorded deaths due to landslides.

Tens of thousands of landslides were generated over 10,000 km^2 of North Canterbury and Marlborough, with the most intense landslide damage concentrated in 3500 km^2 around the areas of fault rupture. Landslides caused major disruption with all road and rail links to Kaikoura being severed. Several parts of State Highway 1 and the South Island main trunk railway between Ward in Marlborough and Oaro in North Canterbury were closed due to landslides.

The mapped landslide distribution reflects the complexity of the earthquake ruptures. The landslides are distributed across an elongated area consistent with the area affected by fault ruptures and intense ground shaking. The largest landslides triggered by the earthquake are located either on or adjacent to faults that ruptured to the ground surface. Initial results from our landslide investigations suggest that predictive models relying only on ground-shaking estimates may underestimate the number and size of the larger landslides that occurred.

1 INTRODUCTION

The Kaikoura Mw7.8 earthquake struck at 12.03 am local time on 14th November 2016 (UTC: 11.03 am 13th November 2016) - a shallow (15 km) magnitude 7.8 earthquake (Mw), with an epicentre located near Waiau in North Canterbury (Kaiser et al, 2017), and strongly shook the

North Canterbury and Marlborough regions of NZ. The strong ground shaking caused damage to buildings and infrastructure across the northeast of the South Island. A consequence of the strong ground shaking was widespread landslides. Given the sparsely populated area affected by landslides, only a few homes were impacted and no deaths from landslides occurred.

GeoNet, the geohazards monitoring programme run by GNS Science and funded by EQC, responds to major landslide events in New Zealand using a set of well-established criteria (Dellow 2001, McSaveney et al. 2010). The Mw7.8 Kaikoura earthquake met several of these criteria, including the presence of consequential hazards in the form of landslide dams and direct damage in excess of $1 M. The landslide response in the first week involved developing an awareness of where landslides had occurred and their relative size and spatial density. Response activities quickly evolved into two work-streams. One work-stream focussed on developing the processes and acquiring data in order to compile a world-class landslide inventory. The other work-stream focussed on landslide dams (landslides blocking rivers and streams and impounding bodies of water) and became an evolving process: from a search task, to a rapid assessment of hazard and examining high hazard dams for consequent risks, and then undertaking more detailed work to survey the most dangerous dams so the consequences of a very rapid (catastrophic) failure could be modelled and used by authorities to monitor and manage the risks.

Compiling landslide inventories from events that generate thousands to tens of thousands of landslides has evolved over the last sixteen years. The challenge is record critical information, especially on location and size, as accurately as possible using the best available source data. This ensures any subsequent work to understand and mitigate future hazards and risks from landslides has a good empirical evidence base. This work is important because it provides the basis for providing advice on longer term measures to manage the risks from landslide hazards, such as rules and regulations in district plans implementing risk reduction measures.

2 KAIKOURA LANDSLIDE INVENTORY

A landslide inventory is being compiled to capture the spatial distribution of landslides triggered by the Kaikoura earthquake, to provide information for recovery activities and to provide a high quality dataset for future research. The inventory captures information on: landslide type (material type and style of movement), landslide magnitude (areal size, and volume where possible), runout (distance the debris travels down slope), activity (whether pre-existing), connection and/or interaction with rivers (e.g. occlusions, blockages, buffered), and method of mapping and source of the data, along with the person who digitised and attributed the landslide (Table 1). Capturing the landslide data is an ongoing process as new information becomes available (e.g. satellite images, LiDAR survey data). Once the inventory has been completed it will be uploaded to the NZ landslide database maintained by GNS Science (http://data.gns.cri.nz/landslides).

The compilation of the landslide inventory has or will utilize the following data sources:

- Satellite imagery including: WorldView- 2 (WV2) 2.4 m resolution (multispectral bands). Imagery date: 22 November 2016; WorldView- 3 (WV3) 1.4 m resolution (multispectral bands). Imagery date: 25 November 2016; GeoEye (GE) 2 m resolution. Imagery date: 15 November 2016.
- Low level aerial oblique photographs are also being used to help define the landslides. These photographs (many thousands) have been captured by the landslide reconnaissance team and others post-earthquake, mainly from helicopters. The photographs are georeferenced using a GPS flight track-log, and they cover most of the area affected by landslides.
- Pre- and post-earthquake orthorectified aerial photographs (captured by Aerial Surveys Limited and commissioned by LINZ), 0.3 m resolution.
- Post-earthquake digital elevation models derived from airborne LiDAR.
- Post-earthquake digital surface models derived from stereo satellite imagery (NSF RAPID project).

- Pre- and post-earthquake digital surface models derived from the aerial photographs.

The WV2 and WV3 images (provided by Digital Globe) have been processed by GNS Science. These have moderate positional accuracy and in some mountainous areas the images have been orthorectified using a low-resolution digital surface model. The same images have been processed by EAGLE Technology and these have better relief stretch but poor positional accuracy. The images from the different data sources do not cover the entire area affected by landslides, but together they cover all of the main area affected.

Table 1: Landslide source area attribute table.

Fields	*ObjectID*	Source ID	Primary material	Secondary material
Explanation	*Auto*	A unique number for each digitiser's working copy of the database. Each source area should have a unique number. Number does not have to be unique to the whole database, as 'Originator' field will be used to differentiate duplicate id numbers.	The main material type that failed. This is not the geology or description of the origin of the material, but rather related to the material properties and their genesis (origin) which influence the failure and runout behavior. If it cannot be easily assessed use the 'undifferentiated' term.	If there is a second material type involved which appears to have had a significant influence on the failure or runout mechanics, then can include a second material type. If only one major material type, just leave this field as 'Null'.
Examples		1000.	Rock, clay, mud, coarse clastic (e.g. non-plastic silt, sand, gravel and boulders), peat, ice, undifferentiated.	Same options as primary material.

Landslide style	**Activity/history**	**Connectivity**	**Comment**	**Method & Confidence**
The movement mechanism of the landslide.	Indicates whether landslide appears to be a first-time failure or a reactivation of a previous movement.	This describes the relationship of the landslide debris to streams/rivers or major drainage lines.	Additional notes or clarifications.	Initial mapping method (i.e. imagery etc.) used to digitize the landslide, and confidence in the mapping.
Fall, topple, slide (can differentiate into rotational, planar, wedge), flow (can differentiate into avalanche, dry flow, flowslide, earthflow), slope deformation, or creep. Use 'undifferentiated' if you cannot tell which style of movement.	First-time failure, reactivated, retrogressed.	Uncoupled (i.e. sediment has remained on the slope); Coupled (at least some of the sediment has entered a drainage line (including active floodplain, but **not** including well-vegetated terraces); Blocked (any evidence of blockage even if blockage has since breached).		For each of the methods (Satellite, Orthophoto, Oblique photo, Ground visit, or Multiple [i.e. some combination of these methods]), specify the confidence of the mapping by either 'High' or 'Low'. 'Low' confidence may indicate strong uncertainty in the landslide boundary, uncertainty in the type of landslide mapped, or uncertainty in co-seismic occurrence (in Kaikoura EQ sequence). 'High' confidence can be used if you are fairly confident on the mapping.

Shape Area	***Length***	***Geology***	**Originator**
Auto generated	*Auto generated*	*Will auto generate from QMAP data later*	Who digitized the landslide
			C. Massey

In addition to the satellite imagery, low level aerial oblique photographs are also being used to help define the landslides. They are made available to the mapping team via a geodatabase structure in ESRI ArcMap. The national LINZ 8 m resolution digital elevation model (DEM) covers the entire area affected by landslides and is also being used for the mapping. In addition, a 1 m resolution DEM generated from pre-earthquake LiDAR covers a small coastal strip, but is still useful where applicable. The USGS landslide program team and members of the Landslide GEER (Geotechnical Extreme Events Reconnaissance) team have also contributed their data. These data have been used to generate the initial landslide inventory but this only includes larger landslides and only covers some of the main area affected by landslides. The process for compiling the definitive landslide inventory for the 14 November 2016 M7.8 Kaikoura Earthquake is described below.

To ensure a consistent methodology for capturing landslide information, several feature classes in an ArcGIS geodatabase have been set up, with fields containing drop down (restricted) lists for capturing the key landslide information. After scientists have mapped their respective areas, the data is collated and sent to various parties. A sample of each area is checked by another mapper. Following this, further samples of the mapped data have been targeted for field verification.

For each landslide, the following is being collected:

Polygons:

1. Extent of source area (polygon). Note that as best as possible, this should define the whole source area (not just the exposed source area), and may therefore overlap with the landslide debris.
2. Extent of landslide debris. If debris trails from multiple source areas merge, then the polygons also need to merge.

Points:

3. Landslide crown: A point at the top of the landslide crown/headscarp (highest point).
4. Debris Toe: A point at the distal end of debris tail (lowest down slope point).

Lines:

5. Surface deformation: evidence of surficial cracking (scarps), bulging or other deformation indicating mass movement not captured within the landslide polygon areas. These are potential sites of water ingress during later rainstorm events that may destabilize the slope.

For each landslide, all of these features are linked by a common number assigned to the ‘SourceID’ field within each feature class. If there are multiple source areas linked to one debris trail, each Source ID number is added into the ‘SourceID’ field in the landslide debris attribute table, separated by a comma.

For each landslide source area polygon, as much information as possible is entered into the attribute table (Table 1). There are drop down lists for landslide type information (material type and movement style/mechanism), which are based on the Hungr et al. (2014) classification. There are potentially other terms that can be added later that are not included in the classification. There are also a few landslide types that are rare (such as peat failures) but that have been included for completeness. For the debris trail polygon feature class, and the crown and debris toe points, only the SourceID is used to link to the landslide source area.

In addition to discrete landslides, linear slope deformation indicators (i.e. evidence of incipient failures, such as scarps, anti-scarps, or cracks that occur outside of the landslide polygons), can be mapped using a Surface Deformation feature class. These linear features are attributed with the type of surface deformation (from the ‘Type’ dropdown list). Work areas that cannot be mapped (e.g. due to cloud cover or very poor image quality) are also identified. For these areas, a polygon shapefile (e.g. named ‘obscured areas’) is created that outlines the obscured areas. These areas may be mapped at a later date if suitable imagery becomes available.

3 DISCUSSION

The 14 November 2016 Mw7.8 Kaikoura earthquake generated thousands of landslides and 196 landslide dams. Landslides affected a total area of about 10,000 km^2 with the majority concentrated in a smaller area of about 3,600 km^2. During the Kaikoura earthquake at least 23 faults ruptured to the ground surface or sea floor (Langridge et al., 2017). The observed landslide types correlate to two main types of geologically and geotechnically distinct materials, Neogene sedimentary rocks, and Triassic to Cretaceous Torlesse greywacke (Massey et al., in prep). The largest landslides triggered by the earthquake are located on or adjacent to faults that ruptured to the ground surface and are distributed across a broad area of intense ground shaking rather than clustered around the earthquake epicentre, and their locations appear to have a strong structural geological control (Rattenbury et al., 2006). This suggests that event-triggered populations of large landslides could be used to map surface-fault rupture for previous historical earthquakes in New Zealand (e.g. 17 June 1929 M7.8 Murchison earthquake; Hancox et al., 2002).

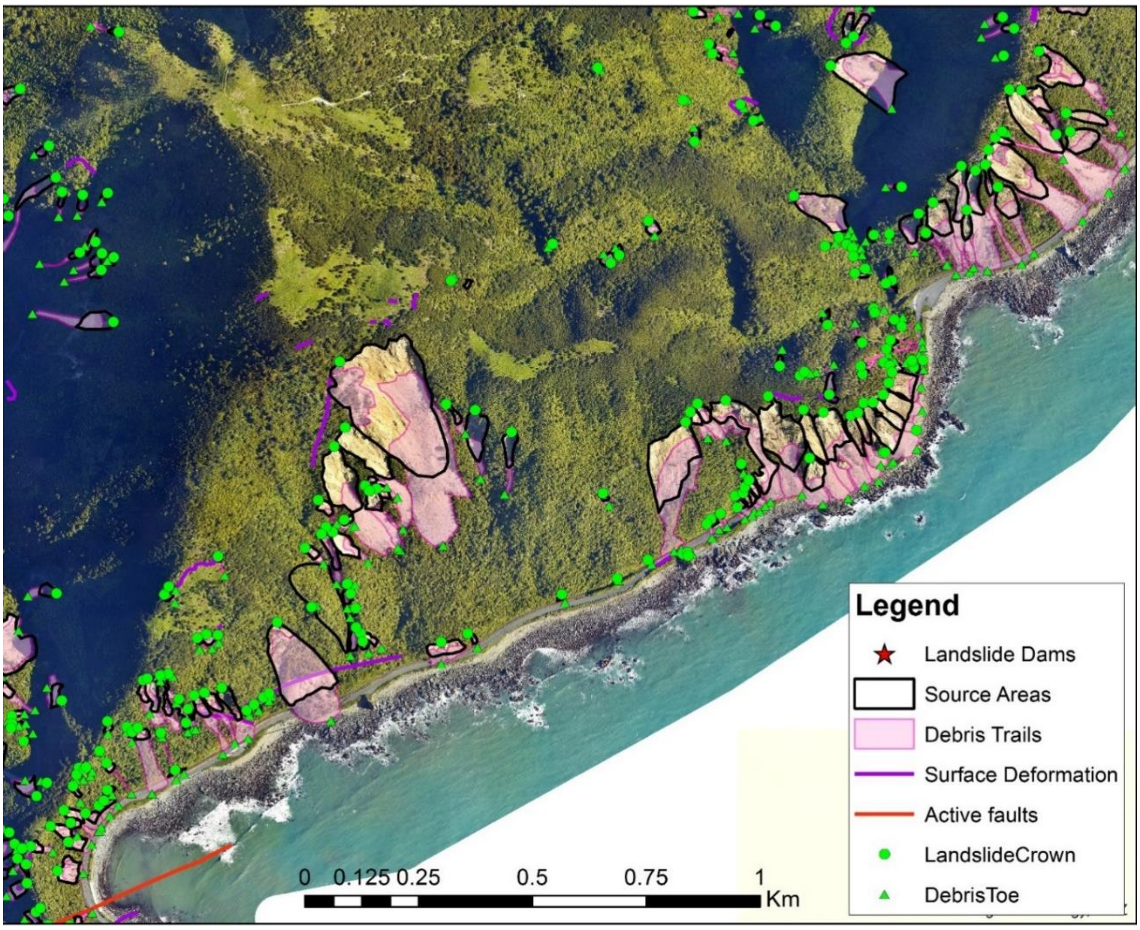

Figure 1: An example of landslide inventory mapping on the coast north of Kaikoura. The large landslides in the centre left of the photo did not reach the foot of the slope during the initial failure and the debris is a hazard that will remobilize in an aftershock or rainstorm and will present an ongoing risk to road and rail users if mitigation measures are not implemented.

The majority of landslides occurred predominantly in two geologically and geotechnically distinct materials, namely: weak to moderately strong (5-50 MPa) Neogene sedimentary rocks (limestones, sandstones and siltstones), and moderately strong to very strong (20-100 MPa) Triassic to Cretaceous Torlesse "basement" rocks (sandstones and argillite). The most frequently occurring landslide types, adopting the scheme of Hungr et al. (2014), correlate to these materials, where reactivated, rock planar and rotational slides tend to be the dominant landslide type in the

Neogene sedimentary rocks, and first time rock and debris avalanches with strong structural geological controls, were the dominant landslide type in the basement materials.

A noticeable feature of this earthquake is the number of valley blocking landslides it generated, which was partly due to the steep slopes and confined valleys in the area, and to the widely distributed strong ground shaking. More than 200 significant valley-blocking landslides triggered by this event have been mapped. The largest has an approximate volume of 23(±2) M m^3 and at least some of the debris from this travelled about 2.7 km down slope where it formed a dam blocking the Hapuku River. There are at least three other mapped valley-blocking landslides with volumes ranging from 2 M to 8 M m^3. Another noticeable aspect of this event is the large number of landslides that occurred on the steep coastal cliffs between Ward, in southern Marlborough, and Oaro, north of Christchurch (Figure 2).

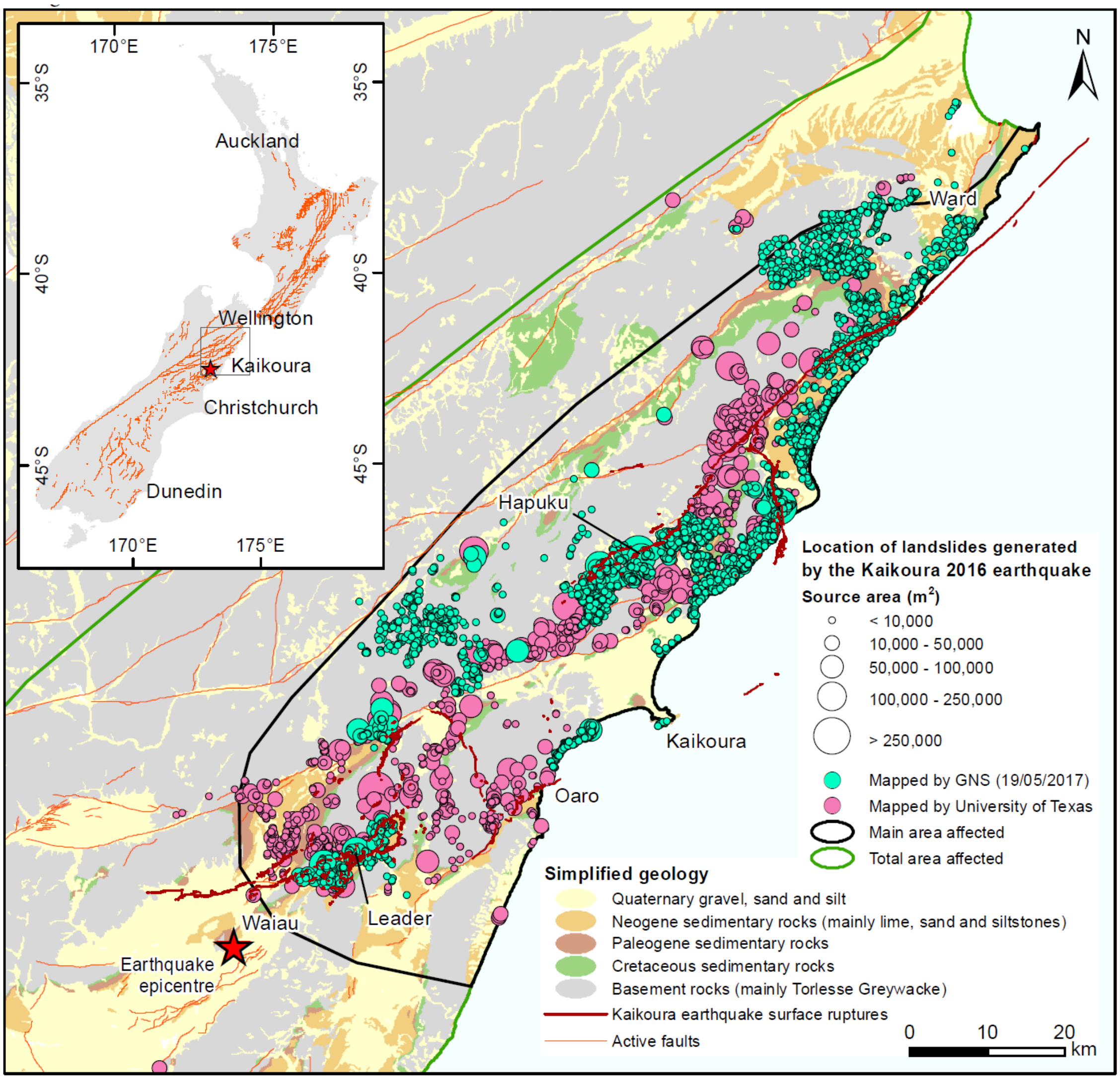

Figure 2: The landslide inventory for the 14 November 2016 Mw7.8 Kaikoura earthquake as at 19 May 2017. The active fault ruptures caused by the earthquake are shown as black lines.

The area affected by landslides is relatively remote with few people living there, and so only a few homes were impacted by landslides; there were no recorded deaths due to landslides. Landslides along the coast, however, caused the closure of State Highway (SH) 1 and the North Line of the South Island Main Trunk Railway, preventing people and goods from entering or leaving the town of Kaikoura, which had a permanent population of about 3,550 people (and seasonally expands due to tourists). These closures led the responsible government agencies to prioritise opening the 'Inland Route 70' to Kaikoura to allow the passage of people, food and water. At the time of writing, the northern section of SH1 from Kaikoura and the North Line of the South Island Main Trunk Railway are both still closed, eight months after the earthquake. The long-term stability of the cracked slopes and the valley-blocking landslide dams during future strong earthquakes and significant rain events are an ongoing concern to the central and local government agencies responsible for rebuilding homes and infrastructure. The number of dams that are of concern is reducing with rainstorm events (particularly in early April 2017) resulting in breaching of four of the dams of greatest concern. Although the direct threat of debris flood hazards from rapid dam breaching is reducing, the longer-term effects of sediment aggradation as landslide debris moves downstream from the steeper in-land slopes to the sea is another ’cascading’ hazard that could pose a risk to agriculture, aquaculture and infrastructure. For example, these cascading hazards will increase river aggradation which will widen river beds, increase bank erosion and consequently increase both the magnitude and frequency of flooding.

The mapped landslide distribution from the Mw7.8 Kaikoura earthquake suggests a complex interaction among earthquake ground shaking, geology and topographic slope angle, which drives the occurrence of the largest landslides generated by this event. Past efforts to explain the spatial variability in co-seismic landslide size and concentration typically rely on comparisons with earthquake magnitude and mechanism, epicentral distance, seismic observations such as peak ground acceleration, peak ground velocity, and engineering parameters such as Arias Intensity and other proxies for ground shaking intensity such as proximity to mapped faults. These factors are then combined with topographic slope angle and geologic information to generate event-based statistical or deterministic models used to explain the distribution of landslide frequency and area or volume. However, most event-based models fail to adequately describe the occurrence of the few relatively large-volume landslides generated by a given earthquake, and in plots of landslide frequency and volume, these landslides are typically outliers. This limits the usefulness of such models for assessing the hazard and geomorphic impacts associated with large co-seismic landslides. A high quality landslide inventory and detailed engineering geological mapping of the largest landslides will allow the interaction between large landslide occurrence and surface fault rupture to be investigated and how the localised release of energy, along with structural geological and material controls and slope morphology interact to initiate large landslides.

The data will be useful for recognizing immediate hazards (potential for failures/reactivations), outburst floods (dam breaches), short- to longer-term potential for debris flow and valley floor aggradation impacts, sediment budgets for catchments, and for assessing landslide causes (i.e. relationships with topography, geology, fault structures, shaking). One of the main uses of this data will be to assess how slopes performed in particular rock and soil (material) types during the earthquake. This data will be especially useful for those similar-sized slopes in Wellington, where much of the city is formed in similar materials (greywacke sandstones and argillite) to those forming the slopes in the, albeit more mountainous, Kaikoura region. Such data will allow us to better constrain the response of the Wellington slopes to strong shaking, e.g. a Wellington Fault earthquake.

4 CONCLUSIONS

Tens of thousands of landslides were generated over 10,000 km^2 of North Canterbury and Marlborough as a consequence of the 14 November 2016, Mw7.8 Kaikoura Earthquake. The most intense landslide damage was concentrated in 3500 km^2 around the areas of fault rupture. Given the sparsely populated area affected by landslides, only a few homes were impacted and there were no recorded deaths due to landslides. Landslides caused major disruption with all road and rail links with Kaikoura being severed. State Highway 1 (the main road link in the South Island of New Zealand) and the South Island main trunk railway between Ward in Marlborough and Oaro in North Canterbury, were closed because of landslides.

Landslide inventory work after a major natural hazard event is an evolving process. Information is required immediately but creating high-quality empirical landslide inventories takes time and underpins the development of plans and policies to mitigate and manage the risks from slope instability. High-quality empirical landslide inventories are crucial as a baseline dataset against which to quantify changing hazards as rainstorms and aftershocks further alter the landscape. A high-quality landslide inventory will provide a basis for understanding the longer-term impacts of this earthquakes as sediment is washed from slopes and through fluvial systems where bridges and flood protection schemes are at risk of being overwhelmed.

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