Phase I: Reconnaissance report on landslides caused by the 16–18 July 2021 rainstorm in the Marlborough region

A Wolter
AF Boyes
E Choi
BJ Rosser
DB Townsend
S-L Lin
KE Jones

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A Wolter, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand
BJ Rosser, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand
S-L Lin, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand
AF Boyes, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand
DB Townsend, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand
KE Jones, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand
E Choi, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand

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CONTENTS

FIGURES

TABLES

APPENDICES

APPENDIX FIGURES

APPENDIX TABLES

ABSTRACT

An extreme winter storm travelled across New Zealand on the 16th to 18th of July 2021, affecting the Marlborough, Tasman, Nelson, West Coast and Wellington regions. Flooding and landslides resulted in evacuation of numerous communities and damage to transport networks and property in these regions. Multiple roads were closed and houses impacted by landslides, particularly in the Buller River Valley and Marlborough.

Following the storm, GNS Science and Marlborough District Council staff completed reconnaissance in the area to determine the extent of damage from landslides to infrastructure and communities, including a five-hour helicopter flight and three days of detailed site visits and surveys. The site visits involved collecting UAV (drone) imagery to create 3D photogrammetric models, characterising 11 landslides, and assessing the damage and impact to 18 residential buildings, including the state or condition of damage sustained from landslides. In addition, the safety colour tagging and habitability of buildings were recorded.

Analysis of rainfall data indicates that 400–500 mm of rain fell over 54 hours (annual return intervals [ARIs] > 250 years) for most of the Wairau north bank hill country and Marlborough Sounds regions, with localised rainfall intensities exceeding 25 mm/hr in several large areas (ARIs 2–10 years). Antecedent soil moisture conditions were relatively high following frequent rainfall over the previous months. Landslides occurred in all vegetation cover types in areas of high rainfall, including indigenous forest, regenerating indigenous forest and scrub, exotic forestry and pasture. Recently harvested or replanted exotic forest plantations were most susceptible to landsliding, but slopes with exotic forest and pasture, as well as with regenerating indigenous forest and scrub, were also commonly affected.

Debris avalanches and debris flows were the most common landslide types and frequently initiated at the contact between bedrock and overlying colluvium. Many of the observed landslides entrained significant large woody debris, which caused substantial damage to buildings. Of the 18 residential buildings surveyed, 10 were deemed uninhabitable. Fortunately, no deaths or injuries were reported, as most of the affected houses were vacant during the event.

Data collected will be included in the development of a rainfall-induced landslide prediction tool. In addition, the information presented here will be used in combination with numerical landslide runout model hazard intensity outputs (e.g. debris flow height) to develop landslide vulnerability functions for New Zealand buildings. The information may also be used to better understand landslide risks in the study area and aid planning for and mitigating against natural hazards.

KEYWORDS

GeoNet response; landslide; Marlborough; building damage

1.0 INTRODUCTION

An intense winter storm (<10- to >250-year event in study area) travelled across New Zealand on the weekend of the 16th to 18th of July 2021, affecting Marlborough, Tasman, Nelson, the West Coast and Wellington. Flooding and landslides resulted in the evacuation of numerous communities, as well as damage to transport networks and property in these regions. Multiple roads were closed, and houses were impacted by landslides, particularly in the Marlborough Sounds, where over 100 landslides blocked roads and required engineering works. Road access to the Outer Marlborough Sounds was cut off by landslides for at least six months, with repair work ongoing at publication. There were fortunately no deaths or injuries reported.

A GeoNet landslide response was initiated to assist Marlborough District Council (MDC) in completing reconnaissance in the area and to determine the extent of damage to infrastructure and communities from landsliding. This included:

- evaluation of media, including images, news reports, road closure reports and other communications about the event;
- aerial reconnaissance of the area from Wairau Valley to the Sounds to observe and photograph the extent of damage due to landslides; and
- field assessments to evaluate damage to dwellings and roads due to landslides, including impact and landslide runout assessments, as well as Unmanned Aerial Vehicle (UAV, drone) surveying.

This report presents Phase I of our investigations, including information about the rainstorm event and related landslides and damage to assets (i.e. buildings and infrastructure). The report outlines input data and survey methods used to assess landslide distribution and resulting damage, summarises observations made during a reconnaissance flight and field assessments, and briefly discusses how the observations will be used to develop landslide vulnerability models for Aotearoa New Zealand buildings. Regional mapping of landslide distributions and impacts will be summarised in a second Phase II report. The information gathered, together with previous landslide and related asset (i.e. buildings and infrastructure) damage data collected after major storms, can assist the regional council and other end users to evaluate damage from different storm intensities and in planning responses and mitigation measures for future events. This work will help identify and mitigate the risks that climate change and the resulting increased weather volatility pose to lives and property (IPCC [2022]). The field assessments and access to satellite imagery were funded by GeoNet. The reconnaissance flights were co-funded by GeoNet and MDC.

1.1 Geological, Geomorphological and Land-Use Context

1.1.1 Geology

The area of interest (AOI) for this study includes the Marlborough Sounds and Wairau River north bank hill country (Figure 1.1). The physiology of the AOI is generally mountainous in the southwest – the Richmond Range has peaks up to 1760 m high (Mt Richmond, Figure 1.2). The Richmond Range gradually decreases in elevation towards the northeast, becoming part of the drowned river valley system of the Marlborough Sounds (Figure 1.3). Subsidence and northward tilting causing drowning of the Sounds is probably contiguous with subsidence and formation of the Wanganui Basin (and Cook Strait) to the north (e.g. Nicol 2011). The Pelorus River is the main river in this area and has changed course many times. It once flowed south from Havelock through the Kaituna River valley and into the Wairau Valley, but this path was abandoned prior to about 70,000 years ago during the Last Interglacial Stage

(Mortimer and Wopereis 1997; Craw et al. 2007). The Queen Charlotte Sound was also carved by the Pelorus River, and this major valley is now only connected to the Pelorus Sound by a low saddle at Linkwater (see Figure 1.4).

Basement geology comprises NE–SW-trending bands of similar rock types. These range from Early Permian to Early Triassic Brook Street, Dun Mountain-Maitai and Drumduan terrane ultramafic and metamorphic rocks in the west and Caples terrane schist in the centre of the area to Late Triassic to Early Cretaceous Torlesse Supergroup (Rakaia terrane Aspiring and Arapawa lithological associations) schist and semi-schist in the east (Heron 2020). In the south, this sequence is cut by the active Wairau Fault, which is a major tectonic feature that juxtaposes early Cretaceous Torlesse (Pahau) terrane sandstone with thin, overlying Cenozoic ‘cover’ rocks on the south of the fault, against the generally more schistose rocks to the north. Other major faults are shown in Figure 1.1.

Textural subdivision is a useful way to map low-grade metamorphic rocks and major structures within the schist (e.g. Turnbull et al. 2001; Figure 1.1). Textural zones characterise the intensity of metamorphism of basement rocks, ranging from those that retain their primary sedimentary appearance (TZ I) but may have some fine-grained metamorphic minerals present, through increasingly foliated and flattened rocks (TZ II semi-schist and TZ III schist) to those that have lost primary sedimentary structures and grains at the microscopic scale (TZ IV), although some primary sedimentary components may still be visible in outcrop.

Basement rocks in the AOI are relatively deeply weathered, and regolith is thick in places. The deep weathering makes ‘soil’ available for landsliding during high rainfall events, and there are many landslide deposits depicted on the 1:250,00-scale geological map (Figure 1.1). The main rivers have carried eroded sediment and formed alluvial plains and terraces along their lengths. Debris fans are also prevalent on valley sides, resulting from the accumulation of many past debris flow deposits. In the south, the broad Wairau Valley has accumulated Quaternary deposits along its length, grading to Holocene marine and marginal marine deposits at the coast.

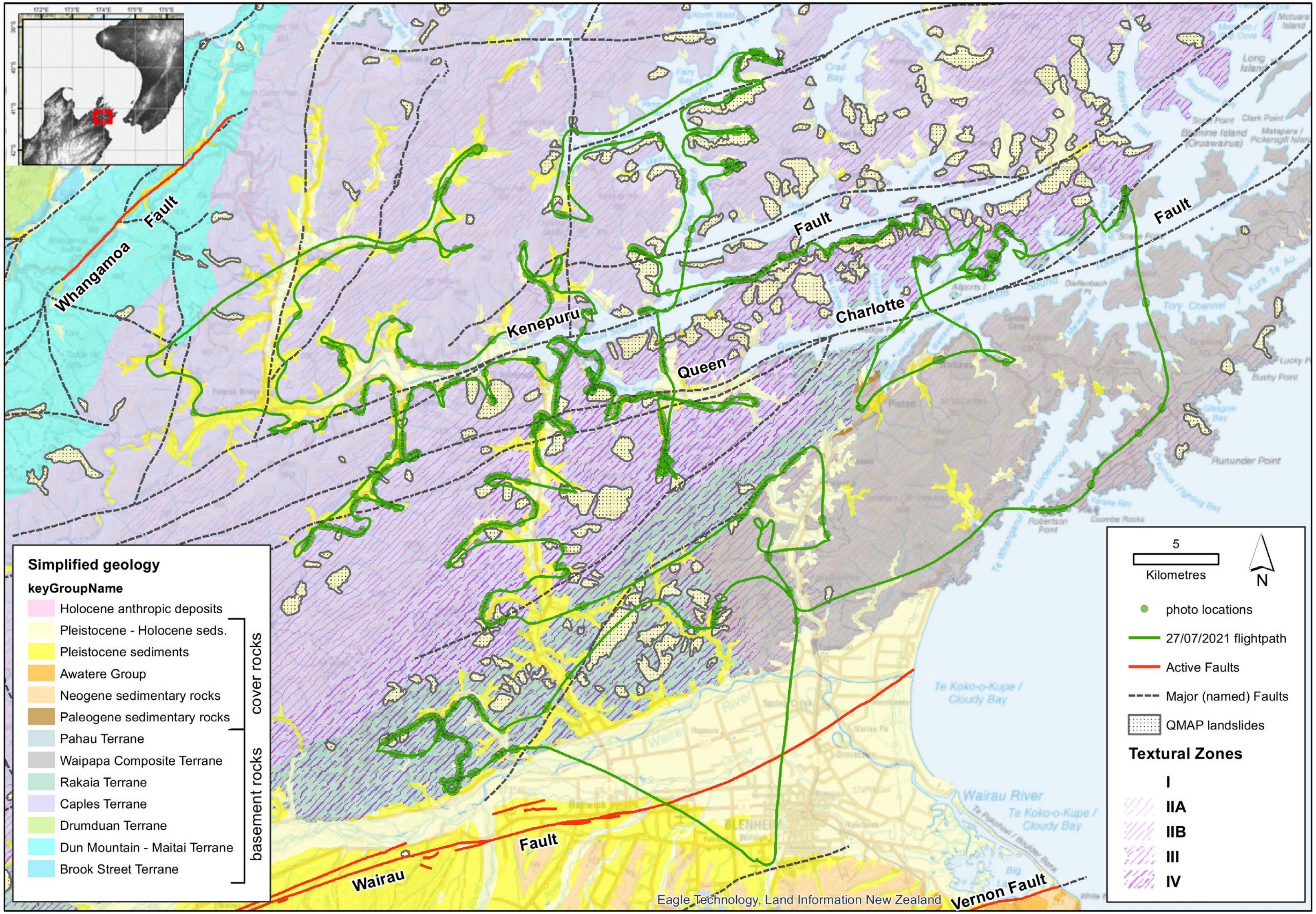

Figure 1.1 Geological map of the area of interest during the July storm event response. Dark-green curve shows flight path of the reconnaissance helicopter flight, and light-green points show locations where landslides were photographed. Refer to QMAP (Heron 2020) for more detailed geological information.

Figure 1.2 View south along Pelorus River, with Richmond Range in the distance.

Figure 1.3 Drowned river valley system of the Marlborough Sounds. Right: Tory Channel with Arapaoa Island.

Figure 1.4 Low-lying saddle between Pelorus and Queen Charlotte (distant) sounds at Linkwater.

1.1.2 Geomorphology and Land Use

New Zealand erosion terrains were defined by researchers at Manaaki Whenua – Landcare Research in the 1990s. They are based on rock type groupings of Land Use Capability (LUC) units in the 1:50,000-scale New Zealand Land Resource Inventory (NZLRI) (Page et al. 1999). The erosion terrains define land in New Zealand by the erosion processes operating on different rock types, using landform, slope angle and rainfall as distinguishing characteristics (Dymond et al. 2010). The erosion terrains are grouped into eight codes, which correspond to the LUC classes from the NZLRI, categorised from 1 to 8, representing increasing erosion susceptibility, or increasing limitation to land use from erosion (Lynn et al. 2009). The distribution of landforms and erosion terrains in the Marlborough Sounds are shown in Figures 1.5 and 1.6.

The majority of land in the Marlborough Sounds is classed as hilly steeplands (slopes >25°) underlain by schist or greywacke. There are also significant areas of mountain steeplands with very steep slopes (>35°) to the west. Most land in the Marlborough Sounds has an erosion susceptibility class of 7 or 8, indicating that there are significant areas of land that have severe to extreme limitations to land use due to high erosion susceptibility. The reasons for the high susceptibility are the combination of steep slopes, weathered bedrock and the potential for high-intensity or prolonged rainfall events.

Class 8 land is mainly very steep mountain land where the most common limitation to land use is extreme actual or potential erosion, often combined with severe climatic and or soil fertility limitations (Lynn et al. 2009). In the LUC mapping, the actual erosion rating is an assessment based on the magnitude and frequency of erosion features at the time of mapping, whereas potential erosion takes into consideration the predominant land use, magnitude and frequency of storm events in the region, as well as the susceptibility of the land if the present land use were to change (e.g. forest to pasture or forest removal). Class 7 land comprises mainly steep low-elevation slopes where loess overlies a variety of rock types (here mostly schist) and has a high susceptibility to various types of erosion when the vegetation cover is removed. The dominant erosion types on Class 7 and 8 land in the Marlborough Sounds are shallow landslides, debris avalanche, gully and sheet erosion (Lynn et al. 2009).

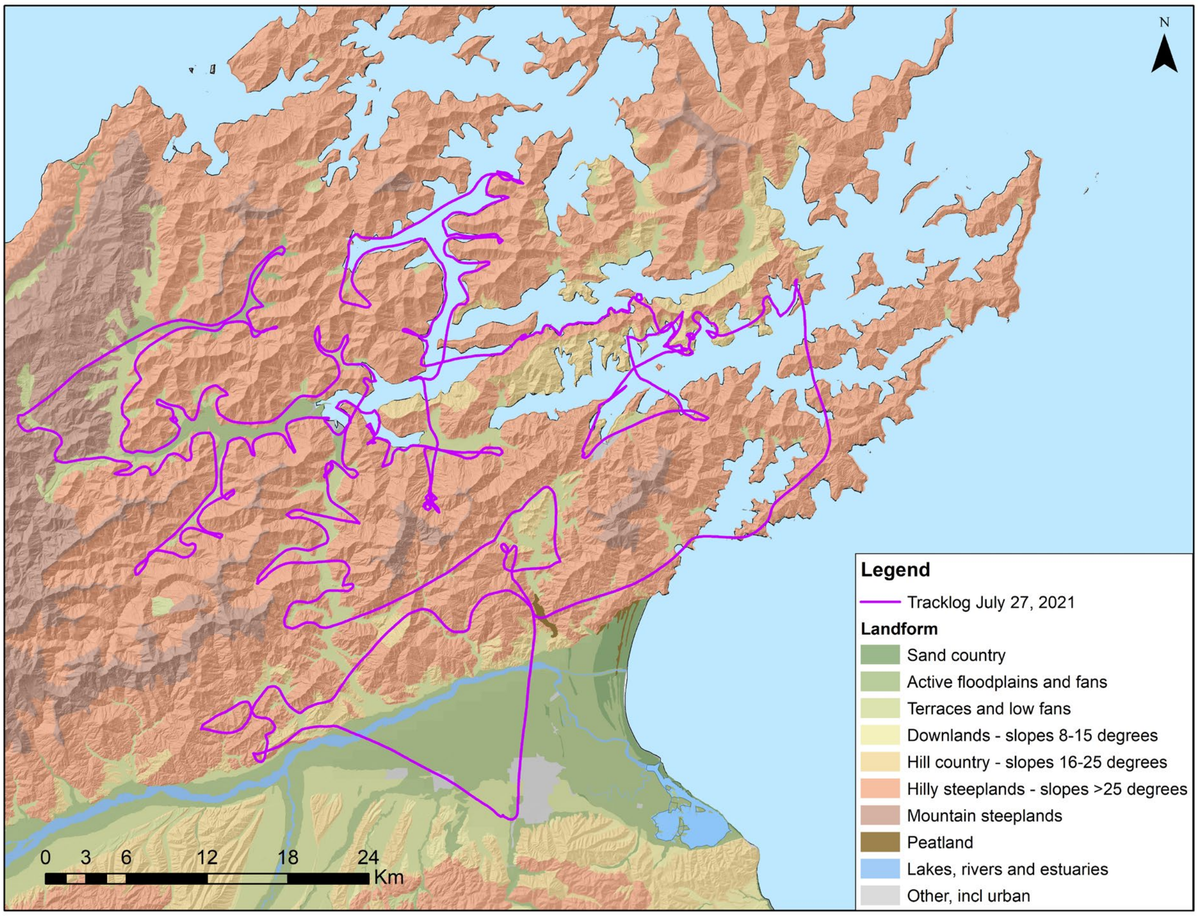

Figure 1.5 Landforms in the Marlborough Sounds and Wairau River north bank hill country, from the Erosion Terrain classification based on LUC units in NZLRI mapping (Page et al. 1999; Dymond et al. 2010).

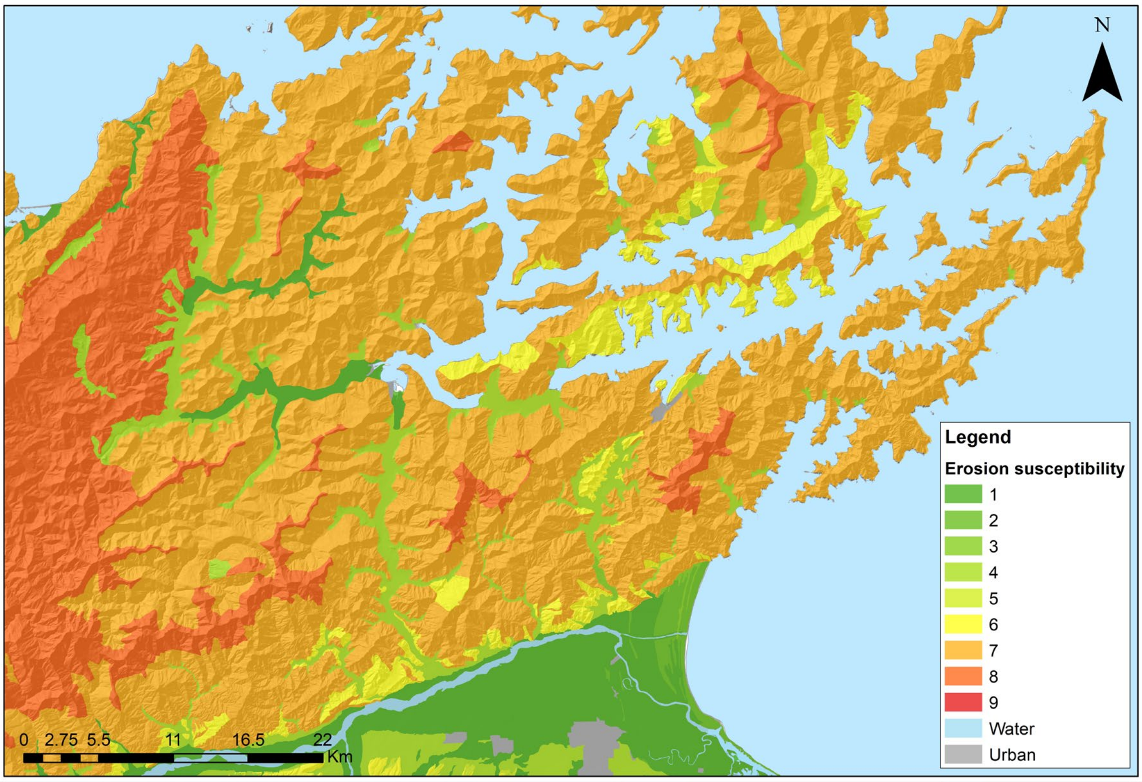

Figure 1.6 Erosion susceptibility of land in the Marlborough Sounds and Wairau River north bank hill country, from the Erosion Terrain classification based on LUC units from the NZLRI mapping (Page et al. 1999; Dymond et al. 2010). Note that the ninth class in the legend is Alpine.

Land cover classes were obtained from Manaaki Whenua – Landcare Research's Land Cover Database (LCDB), version 5.1, as mapped in the summer of 2018/19 (downloaded from lris.scinfo.org.nz/). Land cover in the area covered by the reconnaissance flight is dominated by indigenous forest (approximately 45%, Figure 1.7) and exotic forestry (20%). Exotic grassland (13.2%) and scrub (8.5%) are the other main land-cover types in the hill country. The areas of harvested exotic forest are shown in yellow in Figure 1.7. These areas were updated (in this report) where polygons classified as exotic forest in LCDB v5.1 had obviously been harvested in the 2018/19 LINZ imagery in ArcGIS online (Land Information New Zealand and Sinergise Ltd, Solvenia). In 2019, approximately 90.8 km^2 had been harvested in total (over about the last five years, including the LCDB data and our analysis) and was equivalent to about 4% of the study area.

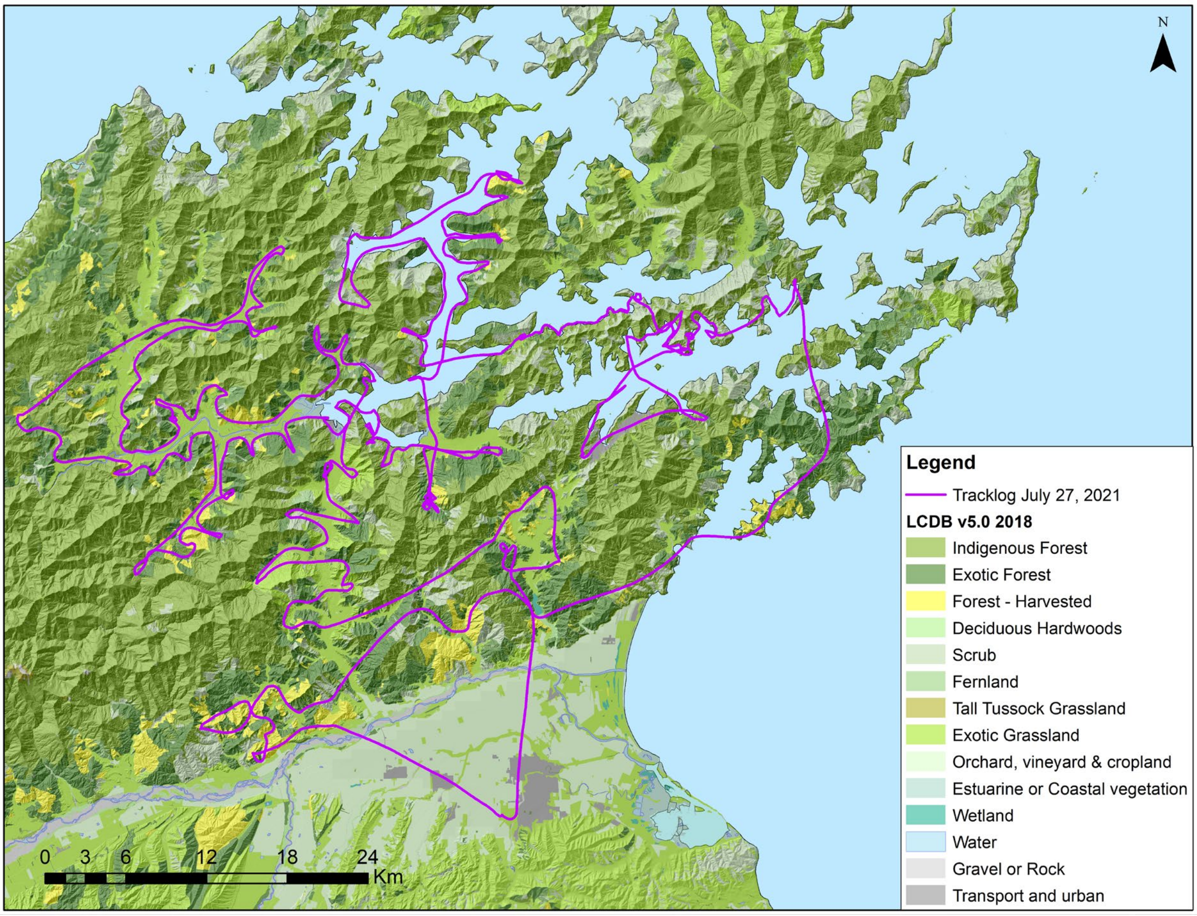

Figure 1.7 Simplified map of land-cover classes from the Land Cover Database (LCDB v5.1). The tracklog from the July 27 reconnaissance flight is also shown.

2.0 DATA SOURCES AND SURVEY METHODS

2.1 Satellite and Aerial Data

The satellite imagery and aerial data available include:

- Sentinel-2 10 m resolution satellite imagery covering the West Coast and Marlborough regions, captured on the following dates:
  - Pre-storm: 23 May; 02, 22, 27, 29 June 2021.
  - Post-storm: 30 July; 01, 03 August 2021.
- Land Information New Zealand (LINZ) 2020 1 m resolution LiDAR elevation data (Digital Elevation Model [DEM] / Digital Surface Model [DSM]), captured by Aerial Surveys between 10 February and 14 August 2020.
- LINZ 0.3 m resolution pre-storm 2015–2017 and 2018–2019 aerial photography.

2.2 Rainfall Data

Hourly rainfall data for the July 16–18 storm were supplied by MetService and MDC rain gauge data (Figure 2.1). Additional rainfall data were downloaded from the National Climate Database (cliflo.niwa.co.nz). The duration of the storm ranged from 54 hours in the Kenepuru Sound area to about 30 hours towards the west of the region (Tunakino, Rai Valley). The maximum rainfall measured over the 54-hour event was recorded at MDC's Top Valley rain gauge (at Staircase Ridge), where 314 mm was recorded over 54 hours; however, gauge-corrected rain radar data from MetService indicate that some areas received up to 400–500 mm over the storm event. The highest storm rainfall total recorded by the rain gauge network in the area covered by the reconnaissance flight was 271 mm at Kenepuru Head, and Ōhinemahuta (Onamalutu Bartlet) received 320 mm over 48 hours. The maximum 1-hour rainfall intensity of 24.4 mm/hr was also recorded at Top Valley, and 21 mm/hr was recorded at Kenepuru Head. The maximum 24-hour rainfall total was 291 mm at Ōhinemahuta (Onamalutu Bartlet), with 282.0 mm at Top Valley, and 242 mm at Kenepuru Head. The rainfall totals at selected rain gauge sites and their corresponding Annual Return Intervals (ARIs) from the High Intensity Rainfall Design System (HIRDS; https://hirds.niwa.co.nz) are listed in Table 2.1. Significant rainfall totals were also recorded at Twin Falls, Mt Stokes, Tunakino and Rai Falls (to the west).

Table 2.1 Rainfall data and annual return intervals (ARIs) for selected rain gauge sites in Marlborough for the 16–18 July 2021 storm. Rainfall data were supplied by MetService, Cliflo and MDC (denoted with *). Sites in bold indicate that both MetService and MDC data are available, and figures in brackets are indicative only. Note that the ARI for rainfall is 36 hours. ARI data were downloaded from HIRDS.

Rain Site	**Rainfall (mm)**			**ARI (Years)**		
	Max. 48 hrs	**Max. 24 hrs**	**Max. 1 hr**	**48 hrs**	**24 hrs**	**1 hr**
Kenepuru Head	271	242	21.0	(~100)	(80–100)/23*	2
Mt Stokes	294	209	N/A	20	10	N/A
Onamalutu Hilltop*	286	193	13.4	215	(290)	<1.5
Onamalutu Bartlet*	320	291	N/A	N/A	(290)	N/A
Rai Falls	279*	208	14.6	20*	5–10	<1.5
Top Valley	309	282.0	24.4	~60	(510)	5
Twin Falls	280.5	200.7	17.2	~30	10–20	<1.5
Tunakino	255	241.5	17.5	2–5	4	<1.5
Wye*	-	96.0	-	-	5	-

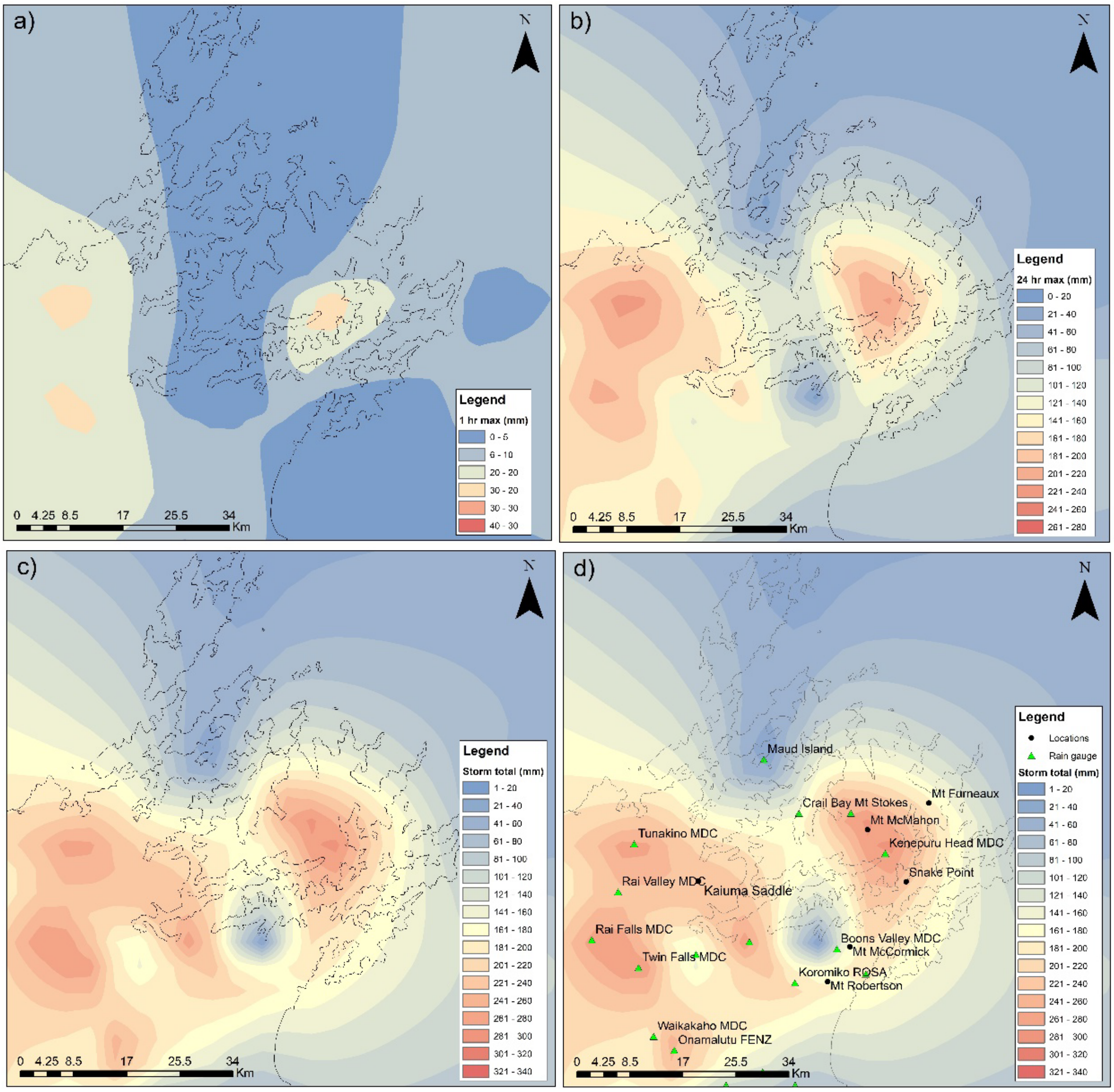

Figure 2.1 Maximum rainfall intensity for (a) 1-hour, (b) 24-hour maximum rainfall and (c) storm total rainfall for the July 2021 storm event, based on rain gauge data. Note that few rain gauge stations have hourly data available. Also shown in (d) is the storm rainfall total in relation to the locations of rain gauges.

Gauge-corrected rain radar data from MetService show the distribution of rainfall estimated by the Wellington rain radar (Figure 2.2). There were large areas where the radar estimated >25 mm/hr that were not sampled by the MDC rain gauge network, including at Kaiuma Saddle (Nydia Bay to Whakaretu Bay, Pelorus Sound), the mountain peaks around Endeavour Inlet (Mt Stokes) and Snake Point.

Maximum 24-hour rainfall totals of 250–350 mm were interpreted by the rain radar for the Richmond Range, the north-bank Wairau hill country (Onamalutu), Kaiuma Saddle and the head of Pelorus Sound, and around Kenepuru Head / Endeavour Inlet (Figure 2.2b). Some isolated areas within these locations may have experienced 24-hour rainfall totals >400 mm. The rain radar also interpreted some isolated areas of higher rainfall on mountain peaks and ridges (e.g. >600 mm in 24 hours at Mt Robertson); however, it is likely that the rain radar over-estimated rainfall in these locations due to the movement of wet foliage in the wind, causing enhanced reflectivities, which are mistakenly interpreted as very heavy rain in the radar processing algorithm (C Noble, MetService, pers. comm. 2022).

Over the 54-hour storm period, there were significant areas where the rain radar interpreted that over 400 mm of rainfall had fallen. These areas include the Richmond Range, Kaiuma Saddle and the head of Pelorus Sound, and the mountains around Endeavour Inlet and Kenepuru Head (Figure 2.2c).

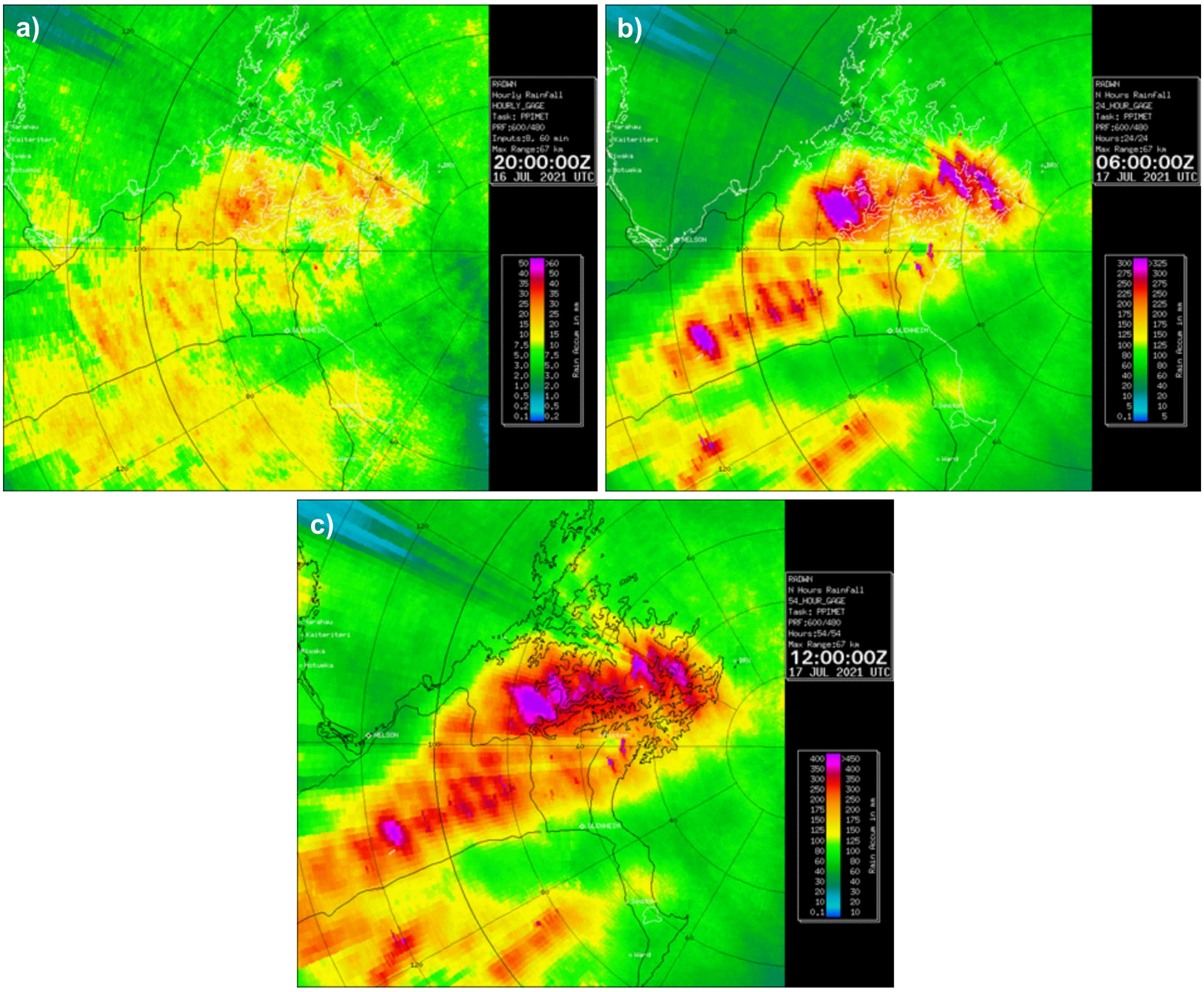

Figure 2.2 Gauge-corrected rain radar image for the maximum rainfall for (a) 1 hour; (b) 24 hours for the 24-hour period until 6:00 pm, 17 July 2021; and (c) the 54-hour storm period until 12:00 am, 18 July 2021. The maximum 1-hour rainfall occurred in the area of Kaiuma Saddle between 19:00 and 20:00 UTC 16/07/2021 (7:00–8:00 am July 17 NZST) and was typically between 25 and 35 mm/hr. The very localised maxima shown near Mt Robertson and Piripi / Mt McCormick are an over-estimation in radar processing due to wet foliage in windy conditions, as described above. The maximum 24-hour rainfall totals were recorded in the areas near Kenepuru Head, Kaiuma Saddle and the Richmond Range. Rainfall totals of >400 mm over 54 hours were also estimated at Kaiuma Saddle and the head of Pelorus Sound, Kenepuru Head and the Richmond Range (figure provided by MetService). See Figure 2.1d for locations.

Data from HIRDS indicate that the storm (24-hour and 54-hour) rainfall totals at Staircase Ridge and Kenepuru Head have ARIs greater than 250 years (Table 2.1). Note that HIRDS reports ARIs up to 250 years, above which uncertainties are large, and ARIs greater than twice the length of the site record should be treated with caution. The 24-hour total at Staircase Ridge also has an ARI of >250 years, and the 24-hour total at Kenepuru Head has an ARI of 80–100 years. Ōhinemahuta (Onamalutu) and Twin Falls showed storm total ARIs of 100–250 years and 80–100 years, respectively. The 54-hour rainfall totals of >400 mm estimated by the rain radar are also well above the 250-year ARI for the Richmond Range and Kenepuru Head. A rainfall total of 400 mm in 54 hours at Kaiuma Saddle has an ARI of ~150 years. These ARIs indicate that this was an extreme and widespread rainfall event in the Marlborough Sounds.

2.3 Reconnaissance Flight

A five-hour, 650 km reconnaissance flight was completed on 27 July 2021 by Brenda Rosser and Dougal Townsend from GNS Science and Matt Oliver from MDC. The purpose of the flight was to investigate and document the extent and nature of landslides triggered by the storm event, and the impacts or damage caused by the landslides. A particular focus was placed on identifying houses or infrastructure that had been damaged by landslides, as there had been several reports of damaged dwellings, and many roads were closed by landslides. The track log of the reconnaissance flight is shown in Figure 1.1 by the dark-green curve, and locations where photos of landslides were taken are shown by light-green points. This gives an indication of the spatial distribution of where landslides were noted, at least along the flight path.

2.4 Field Assessments

Field assessments were conducted on 4–7 August 2021 at sites where dwellings and/or infrastructure were damaged, informed by the GeoNet landslide response reconnaissance flight, as well as by information from Civil Defence and MDC Building Control, and news and social media in the days following the storm. Matt Oliver (MDC) accompanied Andrew Boyes, Sheng-Lin Lin and Andrea Wolter (GNS Science) in the Havelock and Queen Charlotte Sound areas to assess damage to residential buildings, properties and infrastructure.

The approximate locations of site visits are shown in Figure 2.3. Site visits on August 4 and 5 were completed by road using an MDC 4WD vehicle. Much of Kenepuru Road was impassable due to road damage. A MDC Harbours vessel was chartered on August 7 to access damaged homes in Queen Charlotte Sound. Note that August 6 was a poor weather day – no fieldwork could be conducted due to wind and rain.

Tasks completed during the site visits were as follows:

- Record locations of observed landslides on roads, in logging cut blocks and on slopes en route using GPS.
- At each of the detailed investigation sites:
  - survey impacted areas and landslide sources using a UAV (drone);
  - assess dimensions, materials and characteristics of landslide; and
  - assess damage to infrastructure and/or buildings.

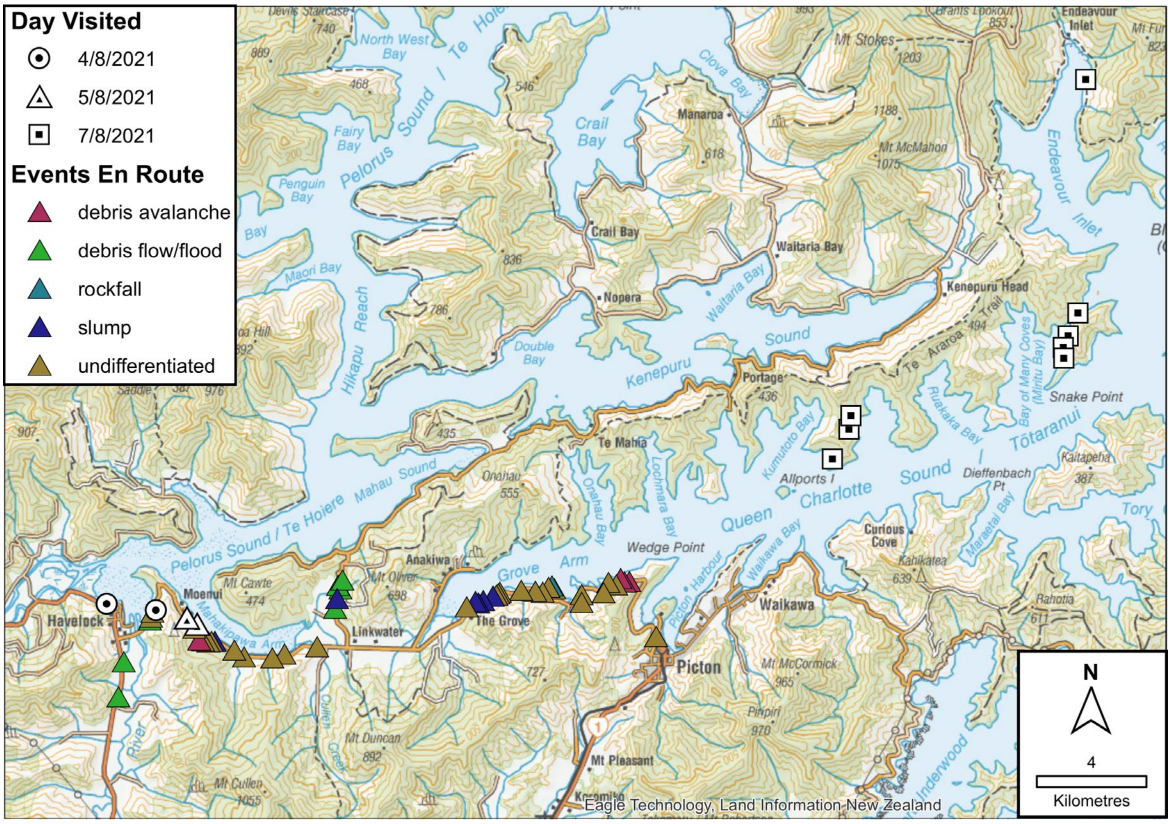

Figure 2.3 Detailed field assessment locations (white and black circles, triangles and squares) and landslides observed en route (triangles coloured by landslide type).

2.4.1 UAV (Drone) Survey

A UAV, or drone, was used to conduct a photogrammetry survey of each landslide that had impacted at least one building. Photogrammetry surveys use large amounts of overlapping photos to create robust 3D models. Typically, they are executed by flying the UAV in automated overlapping grids over the survey area, but, due to several constraints, the UAV operator (Andrew Boyes) chose to fly each survey manually. The primary constraints were a lack of prior knowledge of the survey locations before arriving on site combined with a tight timeframe to survey multiple locations each day. Given the steep terrain at each site, automated grids flown at a single height were impractical within the timeframe. A high density of tree cover surrounding the often narrow landslides made manual flights a favourable solution, as the UAV operator could ensure that photos were collected from view angles that were least obscured by vegetation.

The main issues encountered from manual flight data collection can be a lack of photo coverage in some areas, leading to holes in the 3D model outputs, and a variation in the spatial resolution of outputs. The former issue was avoided by ensuring ample overlap of images taken during flights where possible. The latter issue is unavoidable and common in UAV photogrammetry. The orthomosaics composited from all photos of each survey had a variable image resolution, ranging from 3 to 50 cm/pixel.

The photogrammetry surveys were conducted under Civil Aviation Authority rules part 101. The UAV used was a DJI Phantom 4. Ground Control Points supplied by Aeropoints (Figure 2.4) were used to ensure that each survey was spatially accurate. Where possible, these were placed over the full extent of each landslide, but, in many locations, the source areas and upper debris trails of the landslides were inaccessible. Where this was the case, only the toe and lower areas of the landslide had Ground Control Points placed.

Figure 2.4 Flying the UAV with Aeropoint Ground Control Points (black and white squares), used to georeference the UAV 3D models.

The survey data were processed in Agisoft Metashape (v. 1.6.2). Outputs include a dense point cloud (millions of coloured points) from which a DSM is derived and a textured mesh used to build 3D models and orthomosaics. The 3D models and orthomosaics typically use average ground sampling resolution, with variable image resolution as mentioned above. See Appendix 2 for model details.

2.4.2 Landslide Assessment

At each of the landslide sites, the following information was collected or calculated if relevant to characterise the landslides impacting buildings (see Appendix 4 for details):

- Landslide type (based on Hungr et al. [2014]).
- Source area:
  - source area length, width and depth, area and volume
  - source material (according to New Zealand Geotechnical Society guidelines for material description)
  - future landslide potential, any tension cracks, etc.
- Debris trail:
  - travel distance
  - landslide height (elevation difference between crown and toe)
  - H/L[1] (vertical angle between crown and toe locations).
- Debris inundation:
  - maximum height of main deposit against building, including run-up (e.g. Figure 2.5)
  - cross-sectional area of building impacted by debris.
- Slippage:[2]
  - magnitude of displacement
  - proportion of dwelling moved or undercut by debris movement.

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[1] H/L is the height of the landslide (difference between crown and toe of landslide) over the travel distance (L).

[2] Slippage is defined here as occurring when a landslide undercuts a building.

Figure 2.5 Surveying of landslide debris; measuring inundation along building side. We measured maximum run-up signs (here, above the building windows) not the height of the debris at the time of survey (here, at the base of the windows).

We were unable to visit the source areas of some of the landslides due to time and access constraints.

Using the UAV photogrammetry surveys and the 2020 1 m resolution LiDAR DEMs and DSMs provided by MDC, we created difference models between the pre- and post-storm ground surfaces to calculate landslide area, volume, travel distance, height and H/L. The travel distance and H/L were calculated using the straight-line distance from landslide crown to toe, as well as the steepest path within the landslide debris trail. Uncertainty in volumes calculated is mostly related to changes in vegetation pre- versus post-storm. The sum of the vegetation height was estimated by comparing the 2020 LiDAR DEMs and DSMs. See Appendix 3 for detailed methodology.

2.4.3 Building Survey

The main survey objective was to collect information on building damage due to landsliding. Some general observations about infrastructure (road) damage from landslides were also recorded and photographs were taken. Colleagues at WSP have inventoried the damage to roads and will share the distribution of landslides affecting roads during the July 2021 storm in the Phase II report. The survey team was based in Blenheim and, along with the closures of certain roads (e.g. Queen Charlotte Drive and Kenepuru Road), the travel time to and from the affected areas limited the available field time to collect information about infrastructure assets. Nevertheless, some general observations about road damage from landslides were recorded and photographs taken.[3]

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[3] All photos are supplied to MDC as a digital collection.

In the field, each surveyed building's structural and non-structural attributes and damage were visually inspected from either the street adjacent to the affected building or from the building site (e.g. Figure 2.6). All information collected was recorded via survey forms with pre-populated fields related to building attributes and damage (Appendix 5). A unique, anonymous identifier was assigned to each building. Photographs were taken to record building characteristics and observed damage.

Figure 2.6 Inspecting and assessing structural damage to a home impacted by a debris avalanche.

Structural and non-structural damage was assessed for each surveyed building using ordinal criteria. For structural building damage, the level of damage sustained is expressed in terms of an ordinal categorical variable whereby damage states represent all possible outcomes. This means that damage represented in each state must increase relative to increasing hazard intensity, i.e. no damage to complete damage. This approach is commonly employed in building damage assessments for earthquake and tsunami hazards to support the subsequent development of fragility functions. The structural building damage state criteria developed for the Marlborough landslide survey is presented in Table 2.2. This criterion was informed from previous landslide damage surveys conducted in Napier and Porirua, as well as lessons from the Canterbury earthquake sequence (Massey et al. 2014, 2019).

Non-structural damage in this survey relates to building contents, stock and equipment. Non-structural building components were included in the structural building damage state criteria (Table 2.2). The difficulty of deriving precise estimates of the proportion of damage sustained by non-structural building items relative to their replacement cost (i.e. 'cost of repair' / 'cost of replacement') during field surveys means that ordinal criteria of damage ratio bands were also developed. Where possible, damage ratio estimates were derived based on advice and experiences from property owners or local residents, or, in cases where advice was not available, surveyors inferred damage ratios based on damaged items left *in situ* at the building site or building damage observed.

Residential building habitability was recorded for each building at the time of visit. Residential buildings were deemed either habitable or uninhabitable based on their damage. Building safety inspection by Council (i.e. colour tag, such as yellow [restricted access], red [entry prohibited]) was also recorded if available.

Table 2.2 Building damage state classification used in the Marlborough building survey.

Damage State	Damage Classification	Description of the Observed Damage	Damage Ratio
DS0	None: No damage	Damage is outside building footprint	0
DS1	Insignificant: Minor non-structural damage	Superficial (non-structural) inundation or <10% of building footprint is undercut	0–0.2
DS2	Light: Non-structural damage only	Superficial (non-structural) inundation or <10% of building footprint is undercut	0.2–0.4
DS3	Moderate: Reparable structural damage.	Structural damage or house is displaced	0.4–0.6
DS4	Severe: Irreparable structural damage.	Structural damage or house is displaced	0.6–0.8
DS5	Critical: Structural integrity fails.	Impact induced collapse or >50% of building is undercut	0.8–1.0

3.0 INVESTIGATION OBSERVATIONS

3.1 Reconnaissance Flight

3.1.1 Landslide Distribution and Severity

Observations from the reconnaissance flight indicate that the main types of landslides triggered by the storm event were debris avalanches and debris slides, which often coalesced downslope to form channelised debris flows and floods (see Appendix 1), several of which impacted houses and dwellings (see Section 3.2). Most were shallow (<5 m, Figure 3.1a, b), but several deeper-seated landslides and slumps were also observed (Figure 3.1c), some of which also involved local cracking and slumping (Figure 3.1c). There were several small debris avalanches and slides on the coastal slopes of the Sounds (Figure 3.2). See Appendix 1 for further examples of landslides.

Figure 3.1 Types of landslides observed. (a) Debris slide/flow initiated in shallow regolith, probably at the regolith-bedrock interface, on slopes with established exotic forest cover (Cullen Creek catchment, near Linkwater). (b) Shallow debris flows on recently logged slopes near Onamalutu. (c) Slump in recently harvested area on Daltons Road, Pelorus.

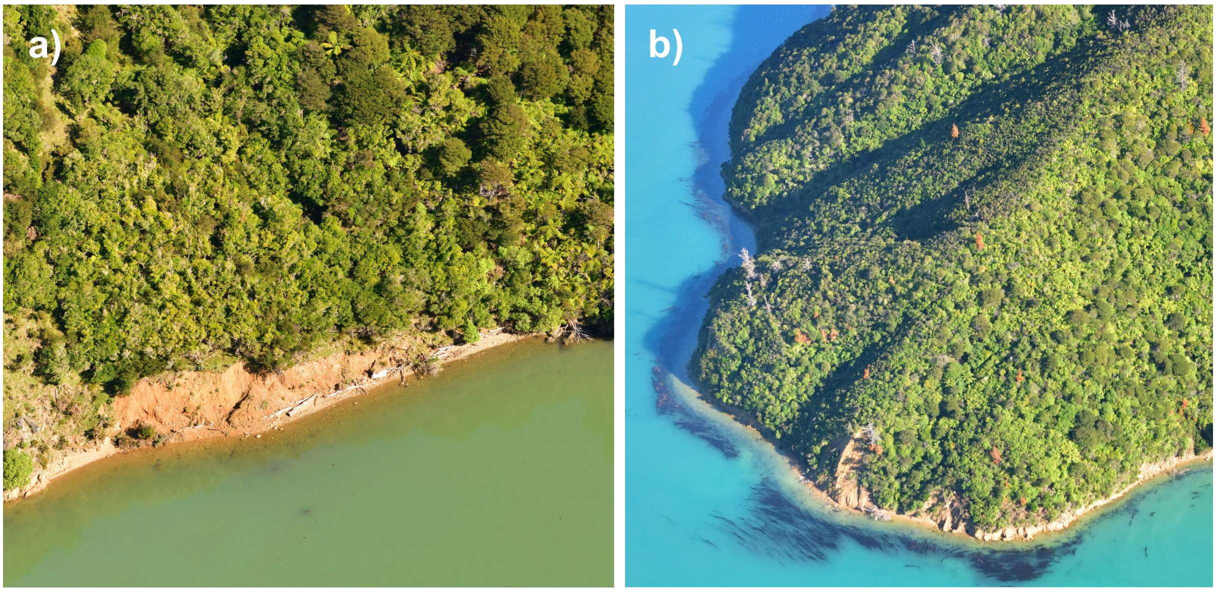

Figure 3.2 Small debris avalanches on coastal slopes in regenerating native bush and scrub. (a) Pipi Beach, Hikapu Reach, Pelorus Sound; (b) Ngaionui Point, Tory Channel.

A preliminary landslide distribution is presented here (Figure 3.3), which was mapped by comparing pre- and post-event Sentinel-2 10 m resolution satellite imagery and pre-storm 0.3 m resolution aerial photography (see Section 2.1 for dates of satellite and aerial photography acquisition). Landslides were also mapped using the oblique aerial photos taken during the reconnaissance flight by MDC staff. Points were located at the highest elevation of the landslide source area. In this report, preliminary observations of the landslide distribution are made. Additional analysis of the landslide distribution in relation to rainfall and underlying topographic and geological factors will be presented in a companion GeoNet landslide response Phase II report. So far, 922 landslides have been mapped as point locations.

Landslides triggered by the July heavy rain were widespread in the eastern Marlborough Sounds, from Okiwi Bay to Tory Channel; however, the highest concentrations of landslides were observed along the north bank of the Wairau River between Bartletts Creek and Kaituna (including Onamalutu) and at the head of Pelorus Sound, near Havelock. Landslides were also common on Arapaoa Island (see Appendix 1).

Landslides occurred on slopes with land cover of exotic forestry, indigenous forest, scrub and regenerating indigenous forest and pasture; however, preliminary observations suggest that the majority of landslides (~60%) were triggered in exotic forestry plantations, including on slopes with established forest (Figure 3.1a), areas that had been recently logged (Figure 3.1b, c) and areas that had been recently replanted. There were considerable numbers of landslides in recently logged areas and indigenous forest near Koromiko and Windermere. In the areas of established exotic forestry, most of the failures appear to have initiated on old skid sites (possibly end-tipped fill) or landings constructed of woody debris and fill or from existing or old forestry roads. These initial findings will be validated and quantified in the Phase II report.

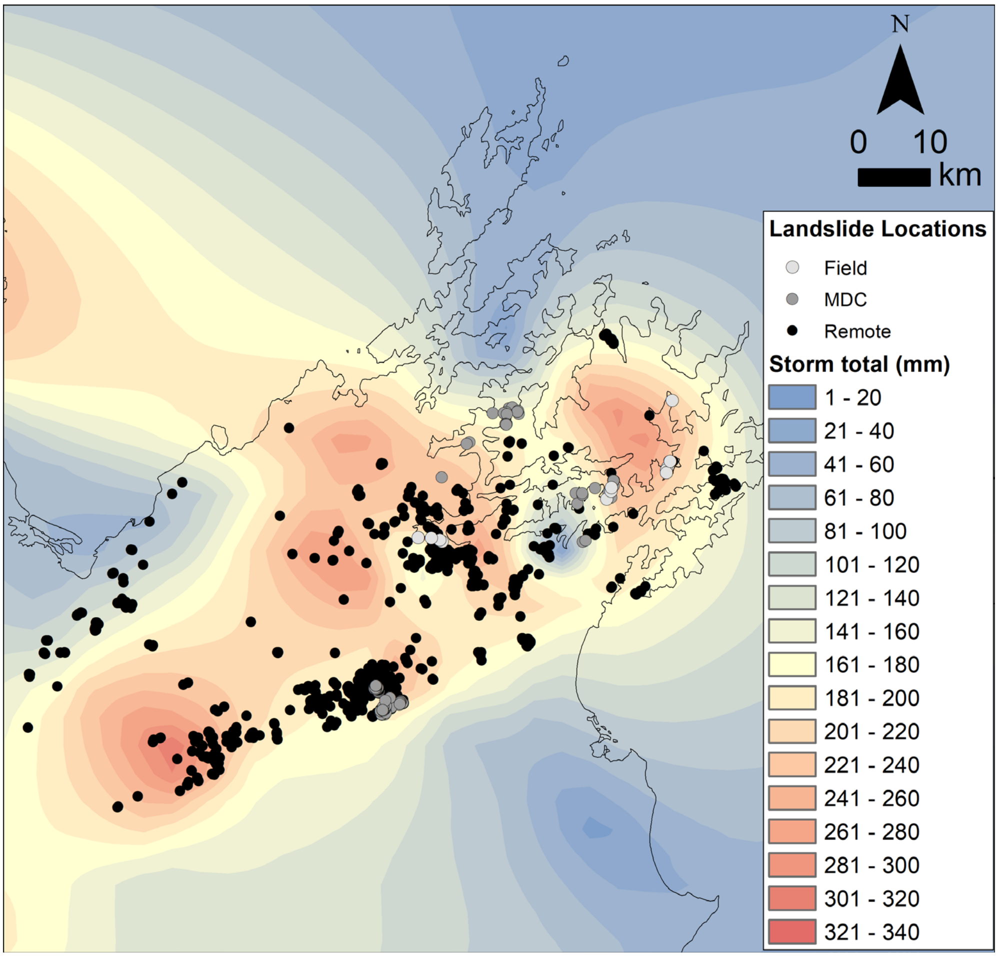

Figure 3.3 Preliminary distribution of landslides triggered by the July 16–18 storm event shown in relation to 24-hour maximum rainfall measured by the rain radar (rain radar data provided by MetService). Also shown are landslide locations mapped by MDC (dark grey) and sites visited during the field assessments (light grey).

There were also a considerable number of landslides triggered on slopes with indigenous forest land-cover types (~21%), particularly on hill slopes west of Picton; and near Havelock, in the lower reaches of the Kaituna River (near Readers Road) and on the south side of Mahakipawa Arm. These areas received the highest rainfall during the storm event. Many of these areas were mapped by LCDB as indigenous forest, particularly in the Pelorus and Picton areas, but were previously used for pastoral farming and have been reverting back to native bush since the early 1980s; hence, there is a mixture of regenerating indigenous forest and scrub in these areas. Many of the debris flows that impacted houses or dwellings initiated in regenerating indigenous forest or scrub. There were relatively few landslides on slopes with old growth indigenous forest, such as in the Wakamarina and Kaiuma Saddle areas, despite some of the highest rainfall occurring there.

Shallow debris avalanches and debris flows were numerous on steep slopes with pasture cover, particularly in the lower reaches of the Kaituna River (near Havelock) and on the south side of Mahakipawa Arm, near Oruapuputa. Landslides estimated to be several tens of metres deep also occurred on pasture slopes in the Havelock area.

3.2 Field Assessments

Figure 3.4 and Table 3.1 show the washouts and landslides noted along roads en route to field assessment sites. Approximately 57 events were observed in recently harvested forestry blocks and on cut and fill slopes adjacent to the roads. Access to much of Kenepuru Road was impossible due to road damage and blockages from landslides; hence, the landslides we observed along the road are only a fraction of the true number. Of the hundreds of landslides initiated along Marlborough road corridors during the storm, over 100 required engineering mitigation and 20–30 are large instabilities that continue to move (D Mason, WSP, pers. comm. 2021). Further analysis of landslide distribution along road corridors will be presented in the Part II report.

Table 3.1 Summary of landslides and related events observed while travelling along roads to landslide sites.

Event Type	Count
Landslide, undifferentiated	32
Debris flow/flood	~8
Slump	8
Debris avalanche	4
Washout	~4
Rockfall	1
Total	**~57**

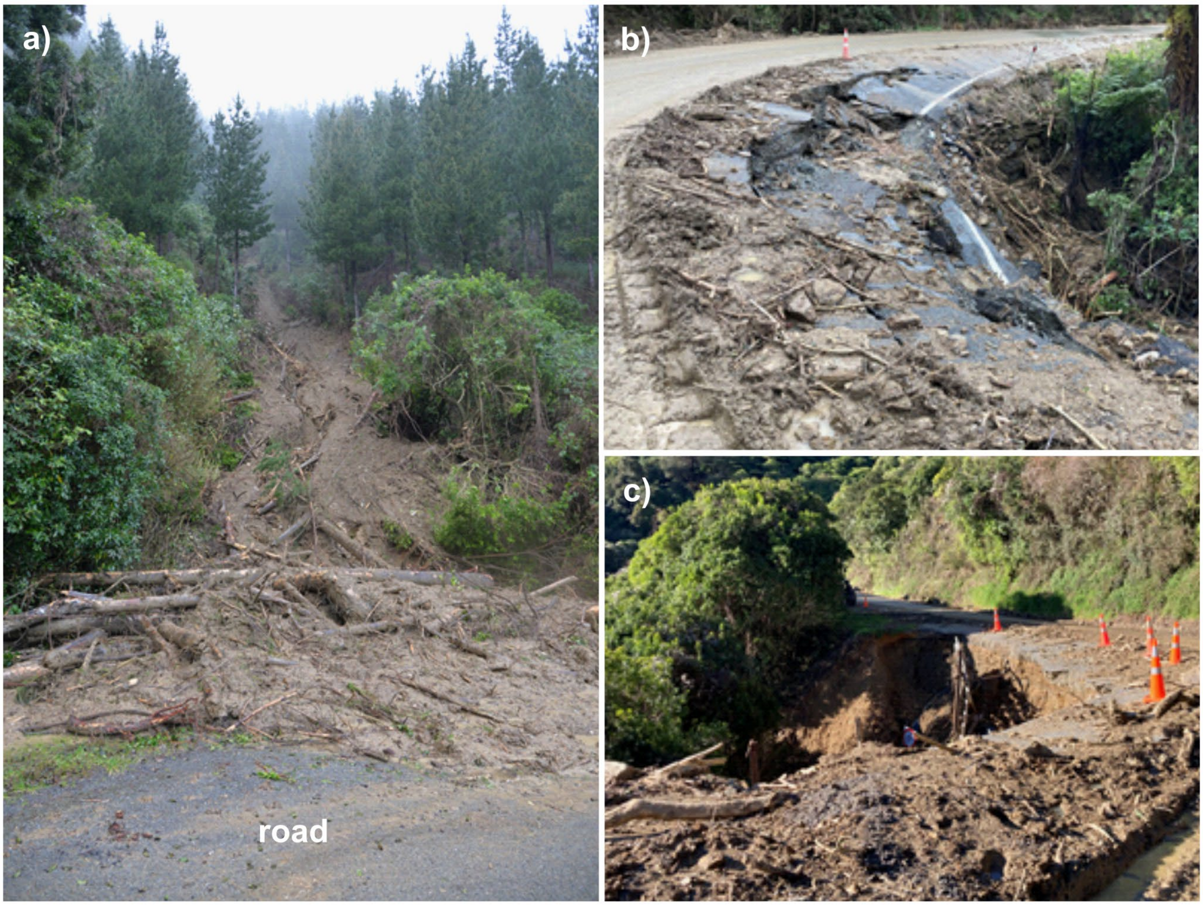

Figure 3.4 Examples of landslides impacting the Marlborough region. (a) shows a debris flow from a channel above the road travelling across and down the road; (b) and (c) show fill slope failures that caused road closures.

We visited 11 landslides that affected 18 dwellings to complete detailed investigations over the three days of site visits. Of the 11 landslides, eight were surveyed with the UAV to produce 3D photogrammetric surface models (Table 3.2).

Table 3.2 Summary of sites visited during the field assessments. 3D model refers to the sites surveyed with the UAV to produce 3D ground models. 'N*' indicates sites where UAV images were captured but did not collect enough data to construct 3D models. See Tables 3.3–3.5 for building damage details.

Landslide ID	Landslide Type	Buildings Surveyed	3D Model
1	Debris flow/flood	3	Y
2	Debris flow	1	Y
3	Debris avalanche	4	Y
4	Debris flow/flood	0	N*
5	Debris flow/flood	3	Y
6	Debris slide/slump	2	Y
7	Debris flow	1	Y
8	Debris flow	1	N*
9	Debris flow	1	Y
10	Debris avalanche	1	N
11	Debris flow	1	Y

3.2.1 Landslide Characteristics

Of the 11 landslides visited, eight were channelised, saturated debris flow-floods that travelled down steep, narrow gullies. The two largest landslides were debris avalanches, and there was one debris slump with slippage.

The five source areas we were able to visit indicated that the failures commonly occurred at the contact between existing colluvium[4] and bedrock. Material was typically matrix-supported[5] (clay, silt, sand) and saturated, with maximum clast[6] length ranging from 50 cm to 1.5 m (Figure 3.5a, b). All of the landslides observed entrained large woody debris, which caused significant damage to several dwellings (e.g. breaking windows and damaging walls). We did not observe or survey any bedrock landslides triggered by the storm, except minor rockfall along roads.

Tension cracks and hanging blocks of material (Figure 3.5a) above most of the headscarps visited indicate that minor volumes of debris may continue to move downslope. The source area of one of the large debris avalanches in the Havelock area was not fully evacuated.

Based on field observations and the differencing between the UAV DSM models and 2020 aerial LiDAR surveys (Appendix 3), landslide source volumes ranged from ~260 m^3 to ~30,000 m^3, whereas debris trail volumes ranged from ~1000 m^3 to ~40,500 m^3 (see Appendix 4). Debris trail volumes were 1.3 to 8 times larger than source volumes, indicating significant entrainment of material as the landslides moved downslope. Three debris flows transitioned into debris floods, with a slurry of silt and water travelling beyond the coarser material deposited by the debris flow.

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[4] Colluvium is any material, usually a range of fine sediments to rock blocks, that has moved downslope.

[5] Matrix-supported material comprises >50% fine material (sand-size and smaller particles), as opposed to clast-supported material (>50% coarse material).

[6] Here, clast refers to cohesive rock blocks, not landslide debris blocks or agglomerate.

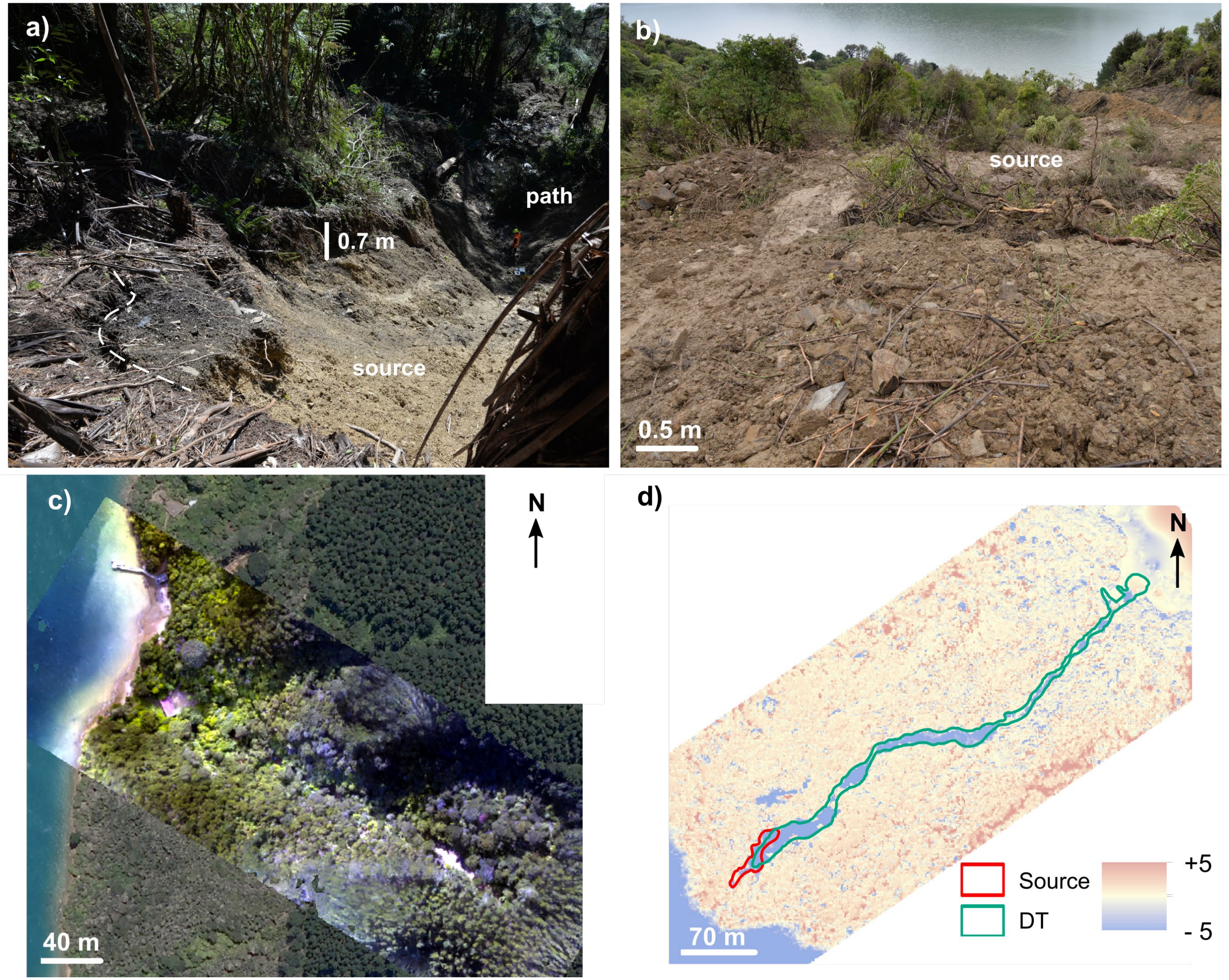

Figure 3.5 Examples of landslides visited during field assessments. (a) Debris flow-flood source area with tension cracks and remaining block above headscarp (dashed white curve). (b) Debris avalanche source area showing texture of material that failed, including blocks and large woody debris. (c) Sample UAV 3D model orthophoto, highlighting the steep, densely vegetated terrain. Source area is a highly reflective area at lower right, and debris travelled to the sea in the existing gully. (d) Sample UAV model – 2020 LiDAR DSM difference model, showing areas of deposition (red), erosion (blue) and the mapped landslide source and debris trail (DT).

3.2.2 Buildings Impacted

Over the three-day survey period, 18 landslide-affected buildings were visited. Over half of them (11) were in urban areas, while the rest were isolated buildings located in Queen Charlotte Sound.

Debris height surveys along the back and side of eight dwellings impacted by landslides indicate that maximum debris heights >1.5 m (debris cross-sectional areas >55% of the wall area) resulted in moderate to critical damage (see Table 3.5). Several dwellings were damaged due to large woody debris transported on the surface of landslides that did not deposit significant thicknesses of material at the building limits.

For each building, structural and non-structural attributes were surveyed (see Section 2.4.3 above), damage was assessed and categorised, and general observations of the building and damage were recorded. The following section summarises the data and observations collected from the landslide-affected buildings. The full dataset is available in Appendix 5.

3.2.2.1 Building Attributes

As the survey objective was to collect empirical information on landslide damage to New Zealand buildings for the purpose of developing landslide vulnerability models, a broad range of building types were visited. A summary of the structural attributes recorded is presented in Table 3.3, with brief descriptions in this section:

1. **Building use:** Residential buildings were the only building use surveyed.
2. **Building age:** Ages of the surveyed buildings were evenly distributed among three house design vintages, namely pre-1960, 1960–1979 and post-1980.
3. **Foundation type:** Timber pile without brace foundations were used for the majority of the buildings surveyed, followed by concrete slab and concrete/steel pile foundations.
4. **Construction type and materials:** Timber-frame is the only construction type for all of the surveyed buildings, which was expected given their residential use. The high proportion of weatherboard or sheet metal claddings for external wall and roof were also expected for typical houses in New Zealand.
5. **Roof frame and slope:** Roof frames constructed of timber material and mild slope (11–30°) were common of all the surveyed buildings.
6. **Storeys:** The majority of the buildings surveyed were single-storey houses.

Table 3.3 Summary of building attributes for landslide-affected buildings surveyed in the Marlborough region 2021.

Building Attributes		**Count**
Age	Pre-1960	7
	1960–1979	5
	Post-1980	6
Foundation	Concrete slab	5
	Concrete rim/perimeter	0
	Rib-raft	0
	Timber pile without brace	8
	Timber pile with brace	0
	Concrete/steel pile	5
Construction type	Timber	18
	Brick Masonry	0
	Concrete Masonry	0
	Tilt-Up Panel	0
	Advanced Design	0
Wall cladding	Weatherboard	14
	Stucco/Roughcast	0
	Brick Veneer	0
	Stone	0
	Fibre Cement Plank	2
	Fibre Cement Sheet	0
	Concrete Masonry	0
	Sheet Metal	2
	Corrugated Iron	0
Roof frame	Timber	18
	Steel	0
	Concrete Slab	0
Roof slope	Steep (>30°)	0
	Mild (11–30°)	11
	Near-Flat (1–10°)	7
	Flat (0°)	0
Roof cladding	Sheet Metal	17
	Clay/Concrete Tile	0
	Metal Tile	0
	Slate	0
	Asphalt and Fibreglass Singles	1
	Sheet Membranes on Plywood Sheet	0
	Concrete	0
	Timber	0
Storey	1	14
	2	3
	3 or more	1

3.2.2.2 Building Impact Data

1. **Landslide type:** Most of the surveyed buildings (11) were affected by debris flow-floods. Five buildings were affected by debris avalanches, while one was affected by a debris slump and one was affected by slippage.
2. **Estimated tag:** To protect human safety, inspection by Council or emergency response personnel resulted in a building being tagged White (W), Yellow (Y1 and Y2) or Red (R1 and R2) (Building Performance 2019).

Table 3.4 Definition of different building colour-tagging categories assigned by Council.

Tag	W	Y1	Y2	R1	R2
Definition	Can be used	Restricted access to part(s) of the property only	Restricted access – short-term entry only	Entry prohibited (at risk from external factors)	Entry prohibited (severe damage to building)

3. **Habitability:** Building habitability was recorded at the time of survey. As the survey was conducted days after event, it is highly likely that many damaged buildings identified as habitable were not inhabited immediately following the event. These buildings are holiday homes rather than first residences.
4. **Estimated damage state:** The damage state criteria presented in the previous section were applied to estimate damage state values for all buildings surveyed. At each location, accessible damaged and non-damaged buildings were surveyed within the time available. Four of the surveyed buildings sustained no damage (DS0), while the damage levels of the remaining buildings were evenly distributed among the various damage states. Selected photographs of surveyed buildings in various damage states are available in Appendix 5.

Table 3.5 Summary of building impact for buildings surveyed in the Marlborough region 2021.

Building Attributes		Count
Landslide type	Debris flow-flood	11
	Debris avalanche	5
	Debris slump	1
	Slippage	1
Estimated placard	None	7
	W	0
	Y1	2
	Y2	5
	R1	0
	R2	4
Habitability	Uninhabitable	10
	Habitable (Occupied)	4
	Habitable (Unoccupied)	4
Estimated damage	DS0 (0); None: No damage	4
	DS1 (0–0.2); Insignificant: Minor non-structural damage	3
	DS2 (0.2–0.4); Light: Non-structural damage only	4
	DS3 (0.4–0.6); Moderate: Reparable structural damage	2
	DS4 (0.6–0.8); Severe: Irreparable structural damage	2
	DS5 (0.8–1.0); Critical: Structural integrity fails	3

3.2.2.3 Summary and Next Steps

Over the three-day period, 18 buildings were surveyed with structural attributes recorded. Section A5.2 presents descriptions of damage for each building surveyed. The damage state of buildings was quantified, along with the damage ratio of building structures, non-structures, contents and stock replacement cost where possible. Similarly, the affected habitability of the building was noted in many cases.

All buildings surveyed were residential with timber construction. Observed building damage was evenly distributed from no damage (DS0) to critical damage (DS5). The empirical building damage data described in this report are intended to support the future development of landslide vulnerability models for New Zealand buildings. Once developed, building vulnerability functions can be applied in risk modelling software to estimate the potential impact and loss sustained caused by landslide hazards in future events.

4.0 DISCUSSION AND CONCLUSIONS

4.1 Rainfall and Landslide Distribution

A significant rainfall event occurred in Marlborough District from 16 to 18 July 2021. As much as 300–400 mm of rain was recorded by rain gauges over 24 hours, and 400–500 mm over 54 hours was indicated by radar for large areas of the Marlborough Sounds and Wairau north bank hill country not sampled by the rain gauge network. Radar data and rain gauges indicate that some areas experienced rainfall intensities of >25 mm/hr. The storm occurred after a prolonged period of rain in the area, hence antecedent soil moisture was high (Wadsworth et al. 2021). ARI of the rainfall totals (for 24-hour and 54-hour intervals) recorded by rain gauge and rain radar were >250 years for many sites throughout the area of interest. ARIs for maximum rainfall intensities (1 hour) were much lower (around 2–10 years).

The extreme rainfall triggered many landslides in the Marlborough Sounds and Wairau River north bank hill country. Landslides were triggered in areas of high rainfall on all vegetation-cover types, including indigenous forest, regenerating indigenous forest and scrub, exotic forestry and pasture. Landslides were most prevalent in areas of exotic forestry that had been recently logged or replanted and were also common in established exotic forest on old landing or skid sites from previous logging rounds, as well as in association with logging roads. Landslides were also common in areas of high rainfall on pasture-covered slopes and on slopes with regenerating indigenous forest and scrub. A preliminary landslide distribution, including 922 features, was mapped using pre- and post-event satellite imagery and aerial photography. Quantitative analysis of the landslide distribution in relation to rainfall, and topographic and physiographic factors controlling landslide susceptibility, will be undertaken in a separate Phase II report to validate the preliminary conclusions presented in this report.

Compared with a previous storm in Marlborough on 28 December 28 2010 (Gray and Spencer 2011), the July 2021 storm was both more intense and of a longer duration. Landsliding appears to have been more widespread in 2021, but LUC classes where landslides occurred and landslide types were observed are the same. Gray and Spencer (2011) reported that forestry tracks, road-cut banks and skid sites were particularly vulnerable to landsliding in 2010. They observed that recently harvested pine or <10-year-old pine plantations were more susceptible to erosion than other land-cover types and that debris flows and debris avalanches were more common on these land use types. LUC classes that were affected were 7e, 8e and smaller areas of 6e (see Figure 1.6 and Section 1.1.2 above for details), indicating that these areas are recognised to have severe erosion risk where there is reduced woody vegetation cover due to highly erodible rock types, steep to very steep slopes and shallow soils. This partly explains why these areas of land were planted in exotic forestry for protection against erosion.

4.2 Landslide Behaviour and Mobility

The landslides that occurred during the July 2021 storm were mainly rapid debris flows, debris avalanches and debris slides. Based on observer accounts, most landslides occurred between 1:00 am and 1:00 pm on Saturday, 17 July 2021, moving from source to toe within minutes. Many debris flows and avalanches also transitioned to debris floods, with finer, silt-sized material travelling farther than the majority of the landslide debris, suggesting that the material was saturated when it failed or incorporated water as it moved downslope. Landslides commonly initiated at the interface between colluvium and bedrock. Tension cracks and hanging blocks at most sites visited suggest that ongoing minor instability could occur, as these landslides undergo minor reactivations and/or retrogression.

The eight surveyed landslides were compared to a global dataset on landslide runout collected at GNS Science (Brideau et al. 2021). The landslide height / travel distance (H/L) is plotted against landslide volume in Figure 4.1, a common method to assess landslide mobility.[7] The six debris flows plot slightly above (n = 5) or below (n = 1) the mean trendline of the global dataset, indicating that they displayed typical to low mobility. The two other landslides also plot above the mean trendline. This suggests that most landslides initiated during the July 2021 storm did not travel as far as expected given their volumes. Landslide mobility was likely limited by impacting dwellings. Entrainment of vegetation and large woody debris may have affected mobility as well. Given the uncertainty in volume calculation due to vegetation, it is possible that volumes were over-estimated. Changes in landslide volume would result in landslide points shifting right or left on the volume versus H/L graph, thus affecting interpretations of mobility.

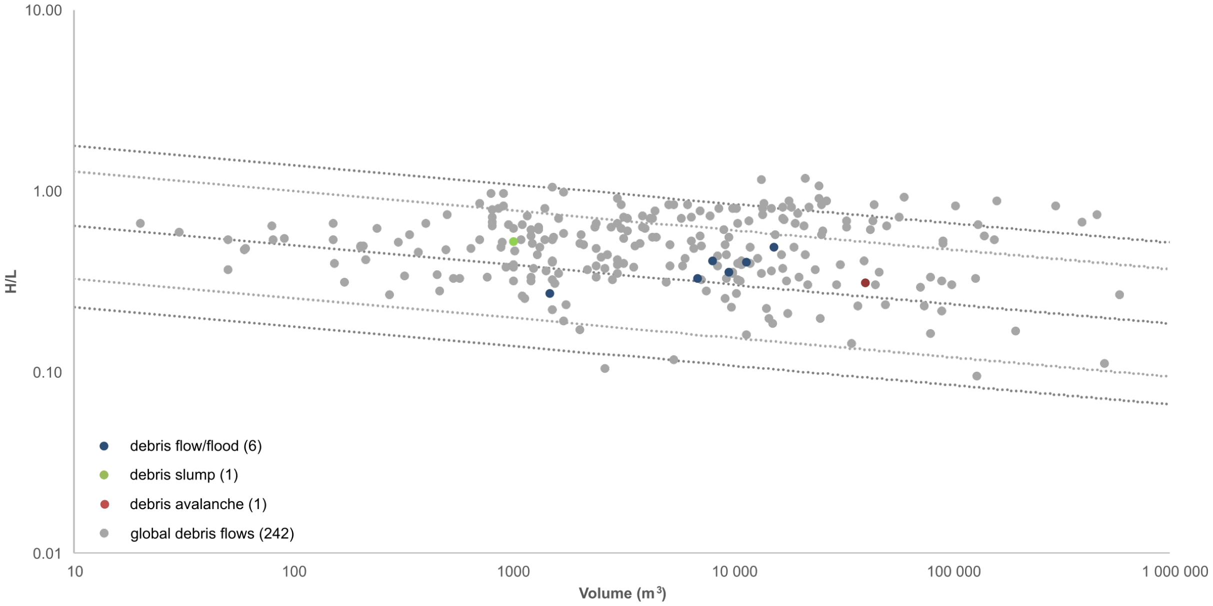

Figure 4.1 Landslides studied as part of the July storm landslide response plotted against existing datasets of debris flows worldwide (Brideau et al. 2021). The dashed lines indicate the mean trendline from linear regression analysis, +2σ and +3σ (standard deviations) and -2σ and -3σ of the global dataset. Numbers in legend refer to counts included in each category.

4.3 Building Damage

The field assessment surveys aimed to enhance the understanding of how New Zealand building assets are damaged by landslides (e.g. debris flows) generated during rainstorm events. The data collected in this study will contribute significantly to the existing limited dataset on landslide-impacted buildings in New Zealand. In this study, we found that debris heights >1.5 m (debris cross-sectional areas > 55% of the building wall area) resulted in moderate to critical damage to buildings. Entrained vegetation caused much damage to buildings (Figure 4.2). Large woody debris damaged windows and house walls, even when non-organic (sediment and rock) debris did not contact the buildings. Large woody debris is often not considered in landslide runout and impact studies.

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[7] Mobility refers to how far a landslide travels (runout distance) relative to the height difference between the crown (top) and toe (bottom) of the landslide and its volume.

Among the 18 surveyed buildings, four of them were classified as R2 colour tagging (entry prohibited, severe damage to building, Table 3.4). They were either buried or washed away by debris or had collapsed (ground floor destroyed by debris). Despite the severe damage, no deaths or injuries were reported, as the houses were vacant during the event. Most of the houses were holiday homes in Queen Charlotte Sound.

Figure 4.2 Damage to a building from large woody debris.

4.4 Future Work and Recommendations

- GNS Science is currently completing landslide polygon mapping using remote imagery and the field observations presented here to better determine the landslide distribution and severity. These data will help to clarify the relationships between rainfall and the resulting landslides in the Marlborough Sounds and will contribute toward a rainfall-induced landslide forecast tool for New Zealand being developed by GNS Science. The landslide distribution will also be analysed in relation to underlying topographic and physical parameters controlling landslide susceptibility.
- The landslide mobility and behaviour data will contribute to a New Zealand runout database, characterising how far landslides travel in different conditions, to ultimately be able to predict runout of future events.
- The information collected on building impacts will contribute toward the development of landslide vulnerability models for New Zealand buildings that relate landslide characteristics (e.g. debris flow height) to asset damage levels or states. These models can be used in risk modelling tools to estimate the potential damage and economic losses for building assets in future landslide events.

- Further investigations on landsliding related to erosion susceptibility in Marlborough are recommended. Updated land-cover and land-use data would be critical to assessing changes in environmental conditions, such as the climate scenarios presented in IPCC [2022].
- Tension cracks and small hanging masses were noted at several landslides investigated after the July 2021 storm, which have the potential to re-activate or fail in the future. Site-specific assessments of these slopes, particularly above dwellings and communities, may be warranted.

5.0 ACKNOWLEDGMENTS

MDC and GeoNet co-funded the joint MDC / GNS Science event response. We thank Matt Oliver at MDC for his collaboration, assistance and input during the investigations and reporting. Landowners graciously gave permission to use the UAV and provided footage of flooding and landsliding affecting their properties during the storms. This footage and their comments have been invaluable in reconstructing event timelines and details. We thank Val Wadsworth (MDC), Chris Noble and John Crouch (MetService) and Saskia de Vilder and Kerry Leith (GNS Science) for their comments during the review of this report.

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APPENDICES

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APPENDIX 1 SELECTED RECONNAISSANCE PHOTOS

Figure A1.1 Channelised debris flow from established forestry, possibly associated with the forestry road or earlier forestry infrastructure (skid site/landing), Ohinemahuta River, Onamalutu.

Figure A1.2 Coalesced debris flow deposits from shallow debris flow/slides on steep pasture slopes at Oruapuputa, south side of Mahakipawa Arm, Pelorus Sound.

Figure A1.3 Debris slide/slump and flow initiated from older forestry landing, Pelorus Sound, near Black Point.

Figure A1.4 Incipient landslide on steep pasture slope showing cracking and minor flow, Cullensville Rd, Linkwater.

Figure A1.5 High-density landsliding on recently logged slopes near Onamalutu.

Figure A1.6 Debris slide/flow on slopes with regenerating indigenous forest and scrub land cover initiated in colluvium in swales or gully heads at Moenui, near Havelock. This area received some of the highest rainfall in the storm event.

Figure A1.7 Mid-slope failures and debris avalanches/flows on newly planted exotic forest slope. Also possibly shows a collapsed landing or skid site. Root raking has occurred up and down the slope, which means that a machine has been down the slope and the surface was likely very disturbed prior to failure.

Figure A1.8 Debris flows on cleared exotic forest slopes near Koromiko.

Figure A1.9 Debris avalanche from a collapsed older landing, constructed from slash and fill, in exotic forestry near Havelock.

Figure A1.10 Landslides initiated from forestry roads and on newly harvested exotic forest slopes near Para.

Figure A1.11 Debris slide/flow on regenerating indigenous forest/scrub slopes. Note also the rotational slump above road (lower right), Mahakipawa Road, Havelock.

Figure A1.12 Deeper-seated landslide and incipient landslide/slump in pasture, also showing cracking, near Havelock.

APPENDIX 2 UAV SURVEY DETAILS

A2.1 Links to 3D Models of Landslides

3D models generated by the UAV survey can be viewed on the GNS Science Sketchfab webpage. These models are private; only those with the link can see them. The Sketchfab models have a lowered resolution to optimise them for viewing over the internet.

Landslide ID 1: https://sketchfab.com/3d-models/marlborough-landslides-lsid1-5c0f5e24eeab484f934c6d7af976d0e2

Landslide ID 2: https://sketchfab.com/3d-models/marlborough-landslides-lsid2-1ab20bd9a3a84d0a9d8a335b07d97a03

Landslide ID 3: https://sketchfab.com/3d-models/marlborough-landslides-lsid3-a4eec8e6a0a94592b4fead6225db20f2

Landslide ID 5: https://sketchfab.com/3d-models/marlborough-landslides-lsid5-88c080f39cc14302a1ef2eafdbc27bb4

Landslide ID 6: https://sketchfab.com/3d-models/marlborough-landslide-lsid6-480c34a1cc9b48779bf835116c5ccf23

Landslide ID 7: https://sketchfab.com/3d-models/marlborough-landslide-lsid7-978a42bea71648a5a121d19ee19e5752

Landslide ID 9: https://sketchfab.com/3d-models/marlborough-landslide-lsid9-24ee59a0b0d54a8da3d5bb6b39bbe758

Landslide ID 11: https://sketchfab.com/3d-models/marlborough-landslides-lsid11-4dfe444c7e4843a48388e175c04550f7

A2.2 Locations of UAV Photos and Ground Control Points

Each figure shows the location of each photo as a grey dot. Ground Control points are shown as blue flags labeled ‘GCP’. These show where an area was not accessible to place ground control points and the density of image data, or lack of, collected for each surveyed area.

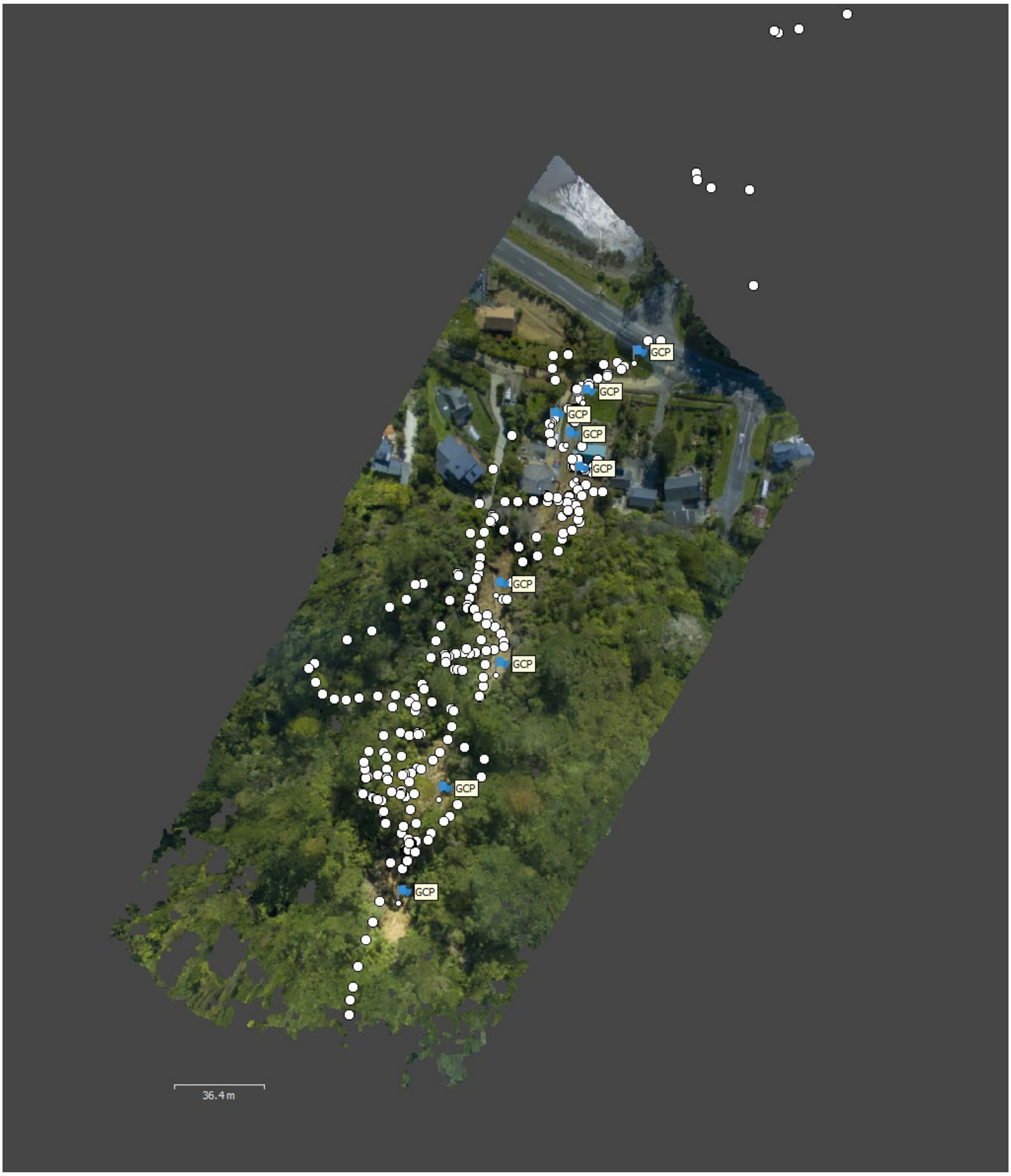


Figure A2.1 LSID1: 285 photos were collected (grey dots); 9 ground control points were used (blue flags).

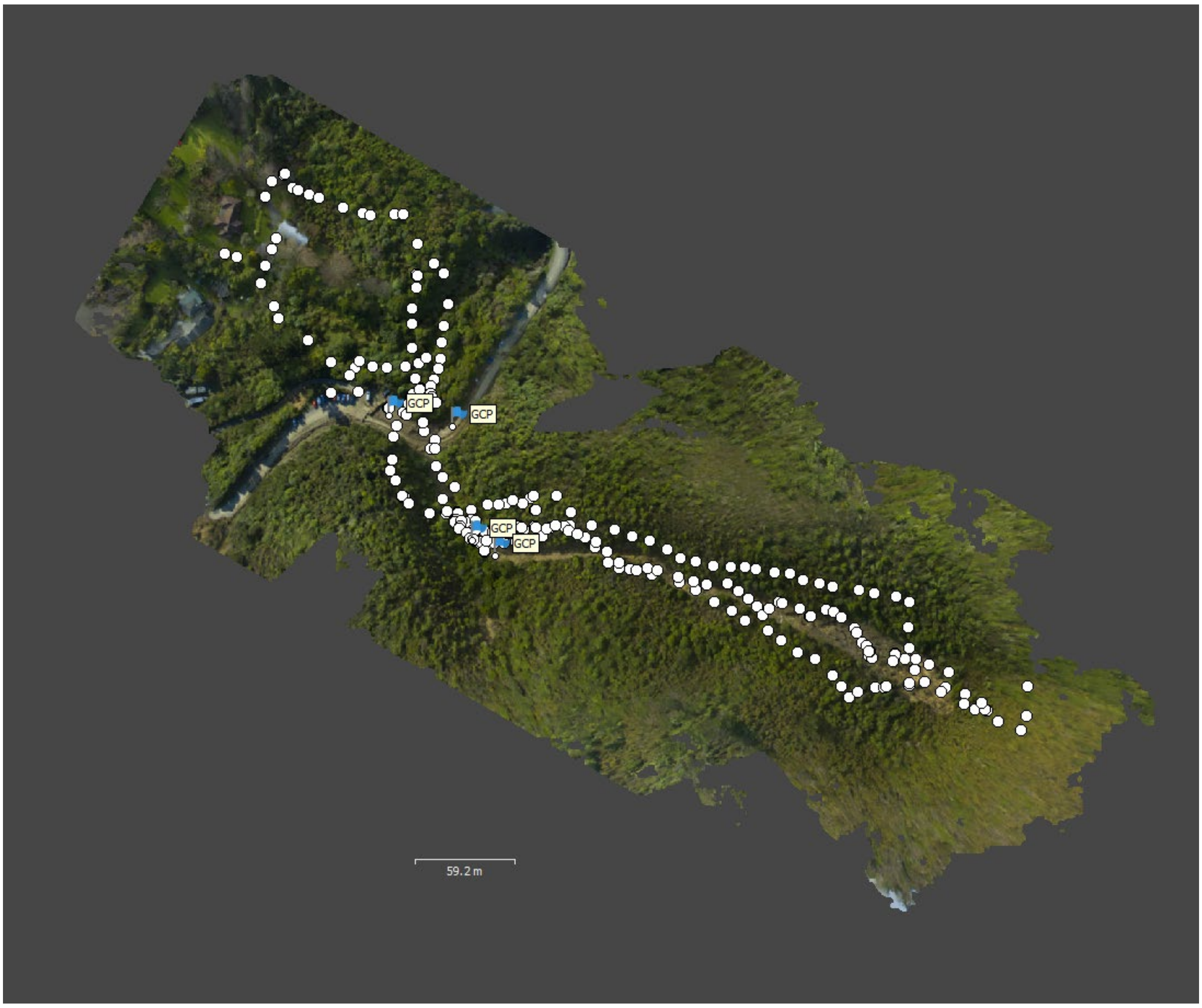


Figure A2.2 LSID2: 288 photos were collected (grey dots); 4 ground control points were used (blue flags).

Figure A2.3 LSID3: 723 photos were collected (grey dots); 10 ground control points were used (blue flags).

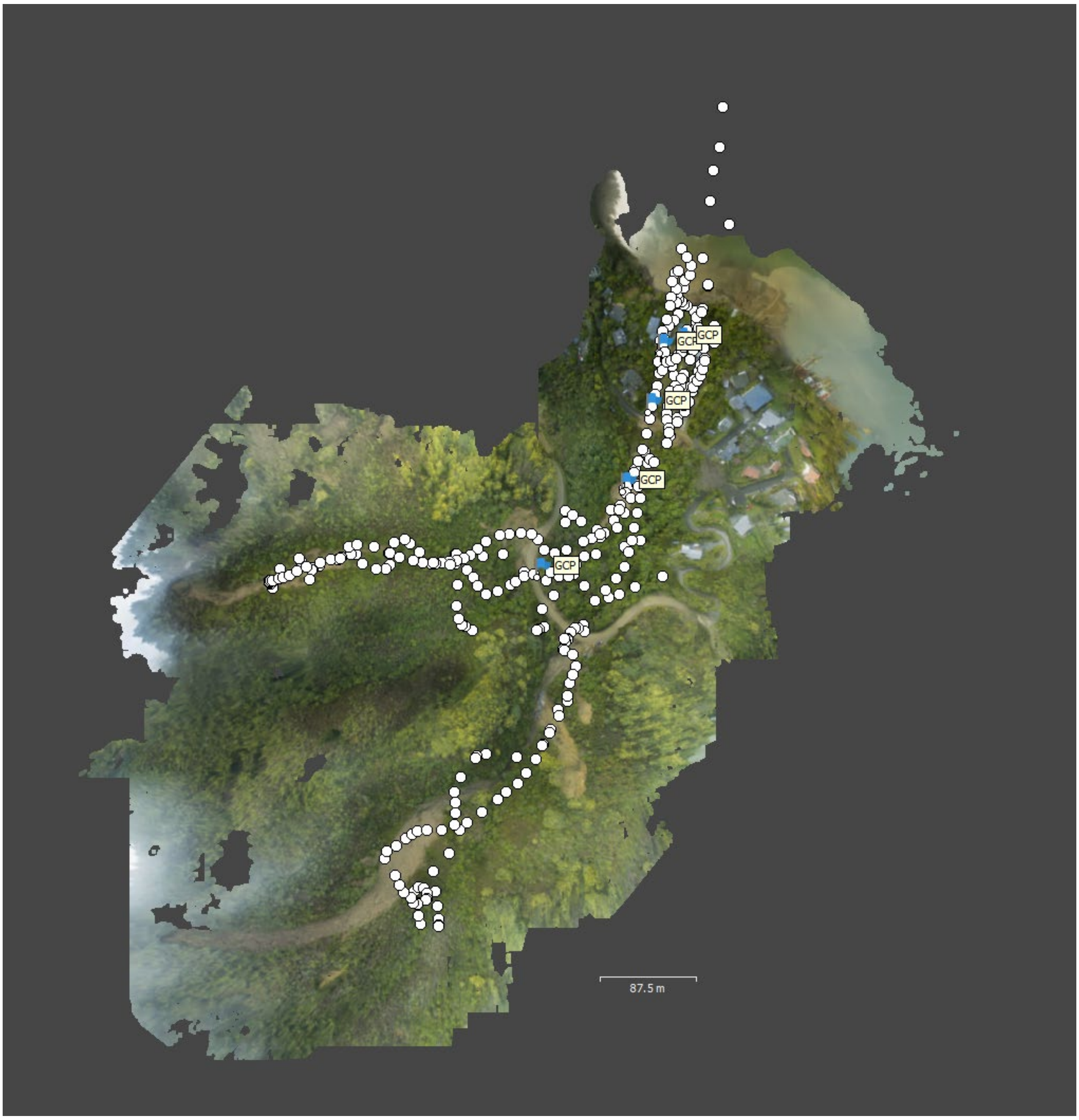


Figure A2.4 LSID5: 384 photos were collected (grey dots); 5 ground control points were used (blue flags).

Figure A2.5 LSID6: 216 photos were collected (grey dots); 5 ground control points were used (blue flags).

Figure A2.6 LSID7: 455 photos were collected (grey dots); 5 ground control points were used (blue flags).

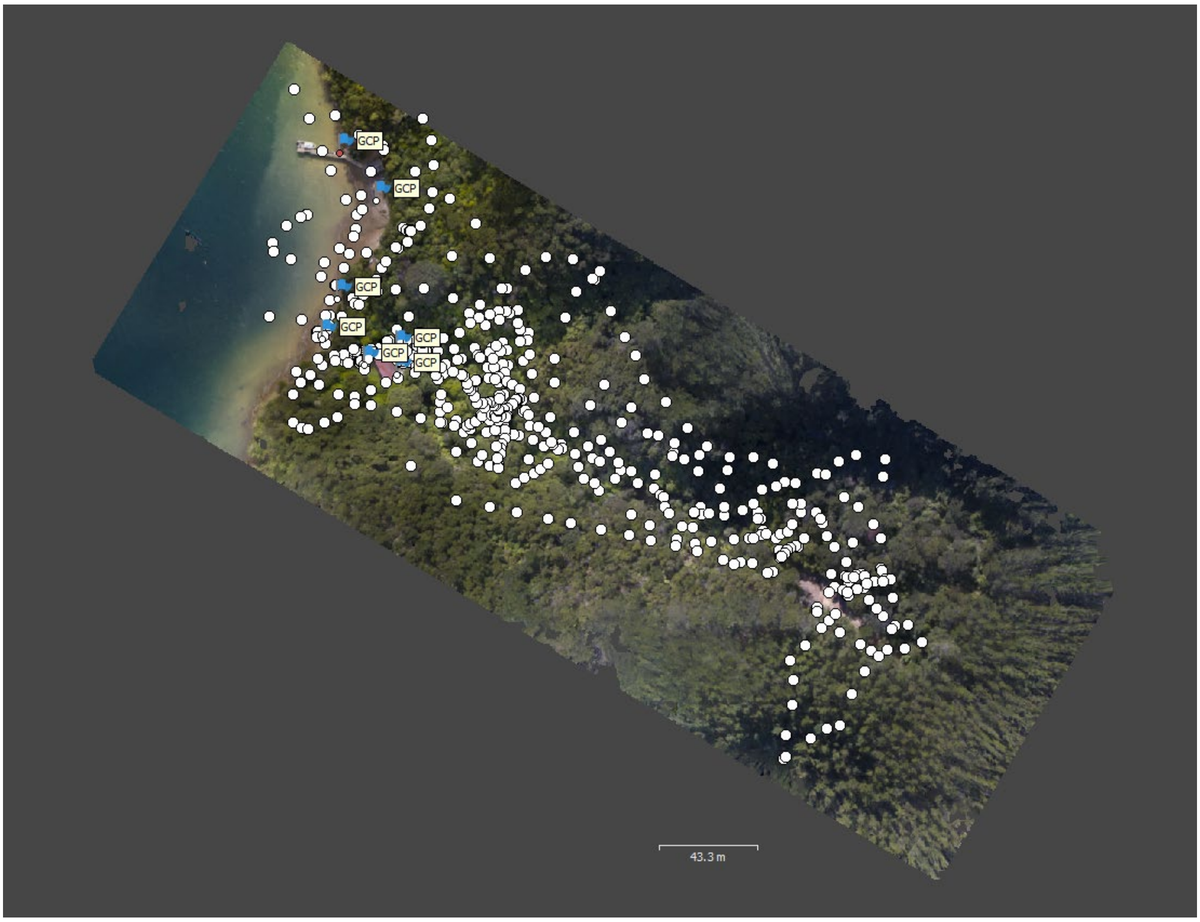


Figure A2.7 LSID9: 573 photos were collected (grey dots); 7 ground control points were used (blue flags).

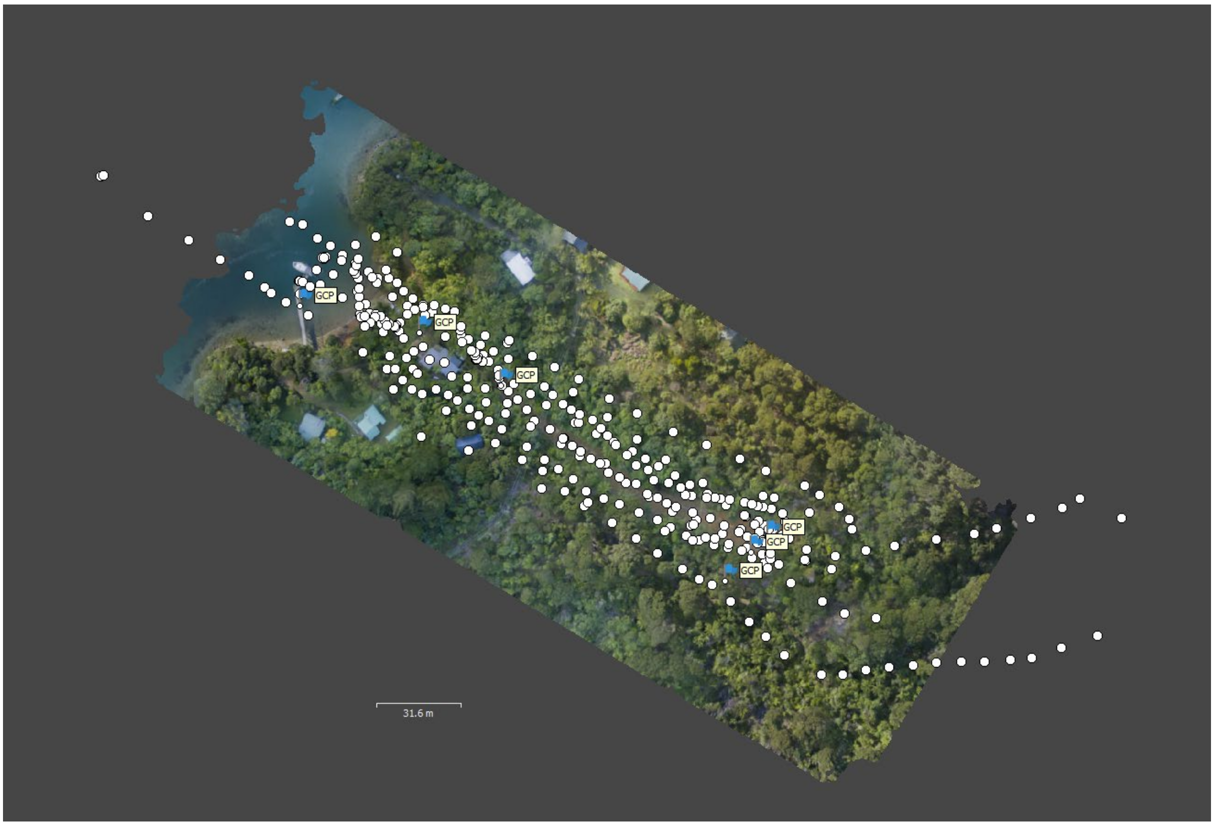


Figure A2.8 LSID11: 346 photos were collected (grey dots); 6 ground control points were used (blue flags).

A2.3 Orthomosaics, Digital Surface Models and Difference Models

Orthomosaics (left panels in Figures A2.9–A2.16) combine all images used in the model to create a mosaic of images draped over the Digital Surface Models (DSMs). DSMs (centre panels of each figure) were generated in Agisoft Metashape from the dense cloud of points for each model. The DSMs have been cropped in the figures to remove anomalous data generated at the outer edges. Source and debris trail polygons from landslides mapped for this study are super-imposed on each DSM. Difference models (right panels below) show erosion and deposition based on comparisons between the 2021 UAV DSM models and 2020 regional LiDAR (see Appendix 3 for methodology). These figures use the Marlborough regional 1x1 m 2020 DSM hillshade in the background.

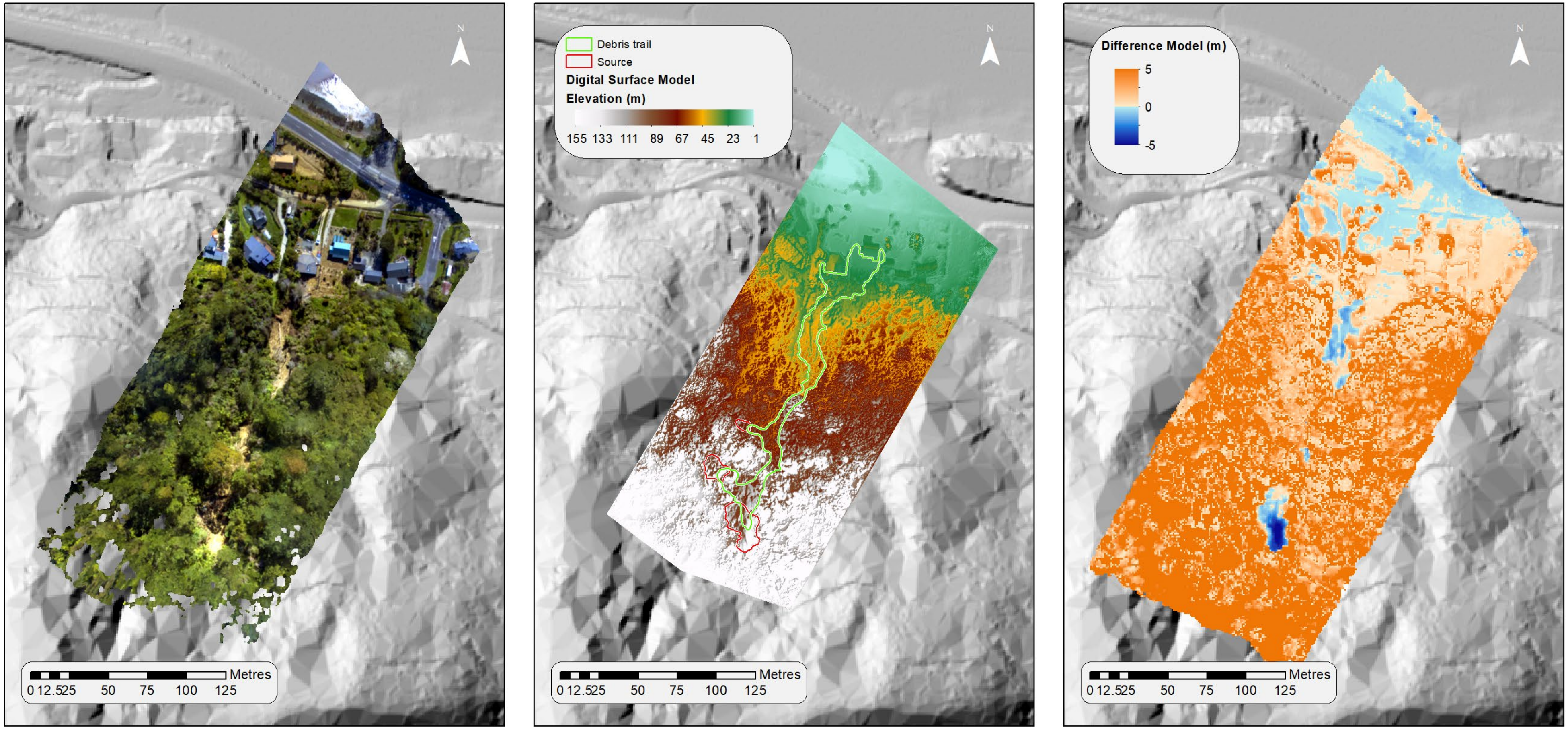


Figure A2.9 LSID 1: (Left) Orthophoto 12279x16593 pixels, 2.34 cm/pixel. (Centre) Digital Surface Model 6872x8993 pixels, 4.68 cm/pixel. (Right) Difference model.

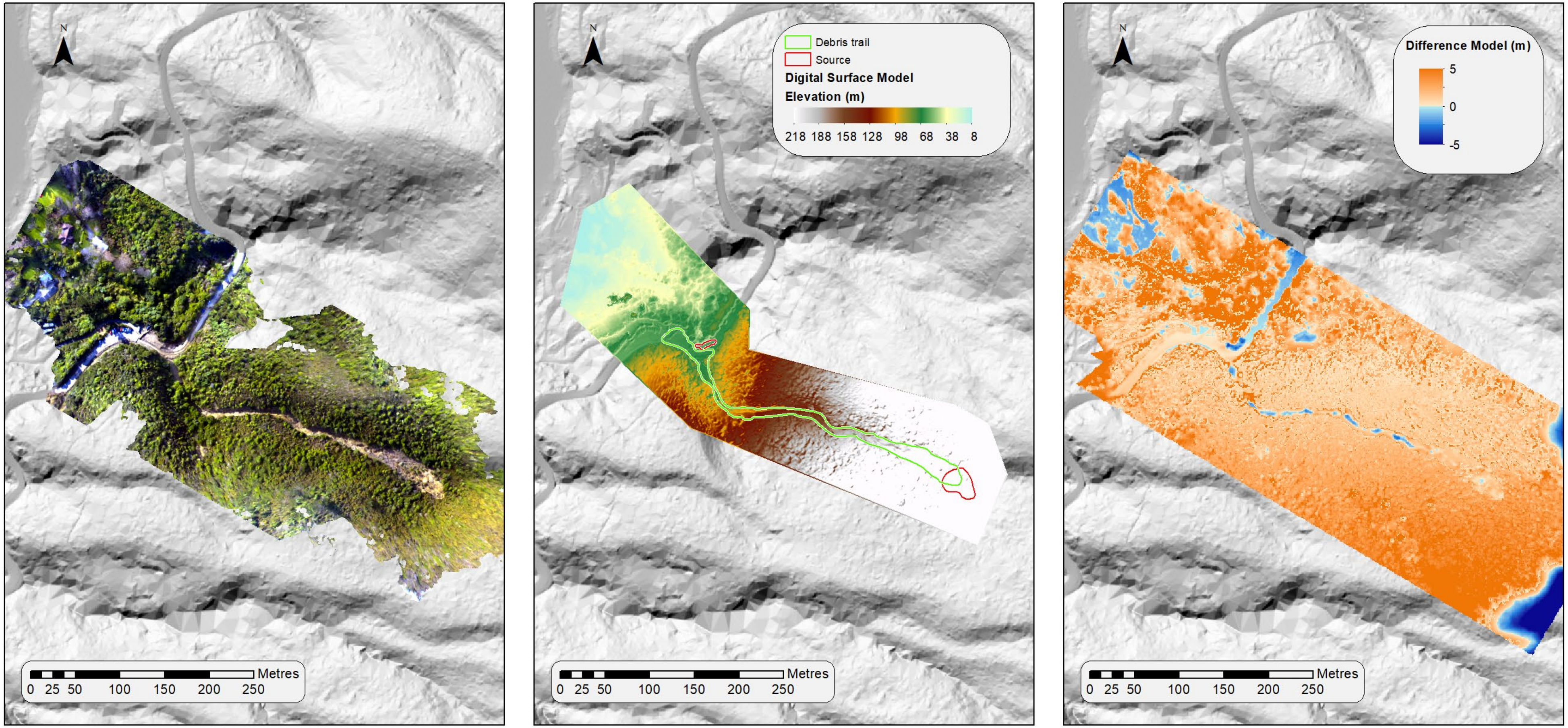


Figure A2.10 LSID 2: (Left) Orthophoto 23181x17659 pixels, 2.82 cm/pixel. (Centre) Digital Surface Model 12755x10100 pixels, 5.64 cm/pixel. (Right) Difference model.

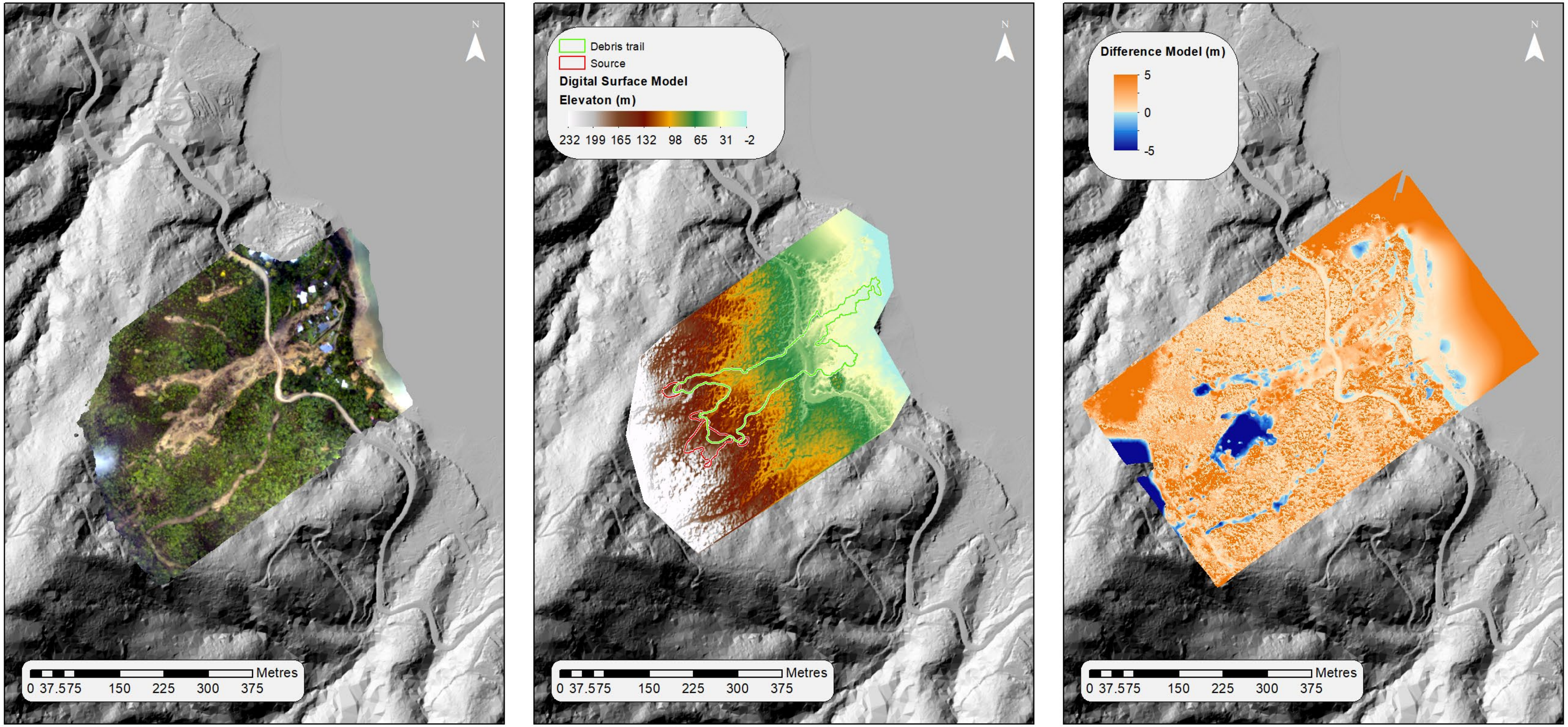


Figure A2.11 LSID 3: (Left) Orthophoto 18368x19495 pixels, 3.12 cm/pixel. (Centre) Digital Surface Model 12495x11486 pixels, 6.23 cm/pixel. (Right) Difference model.

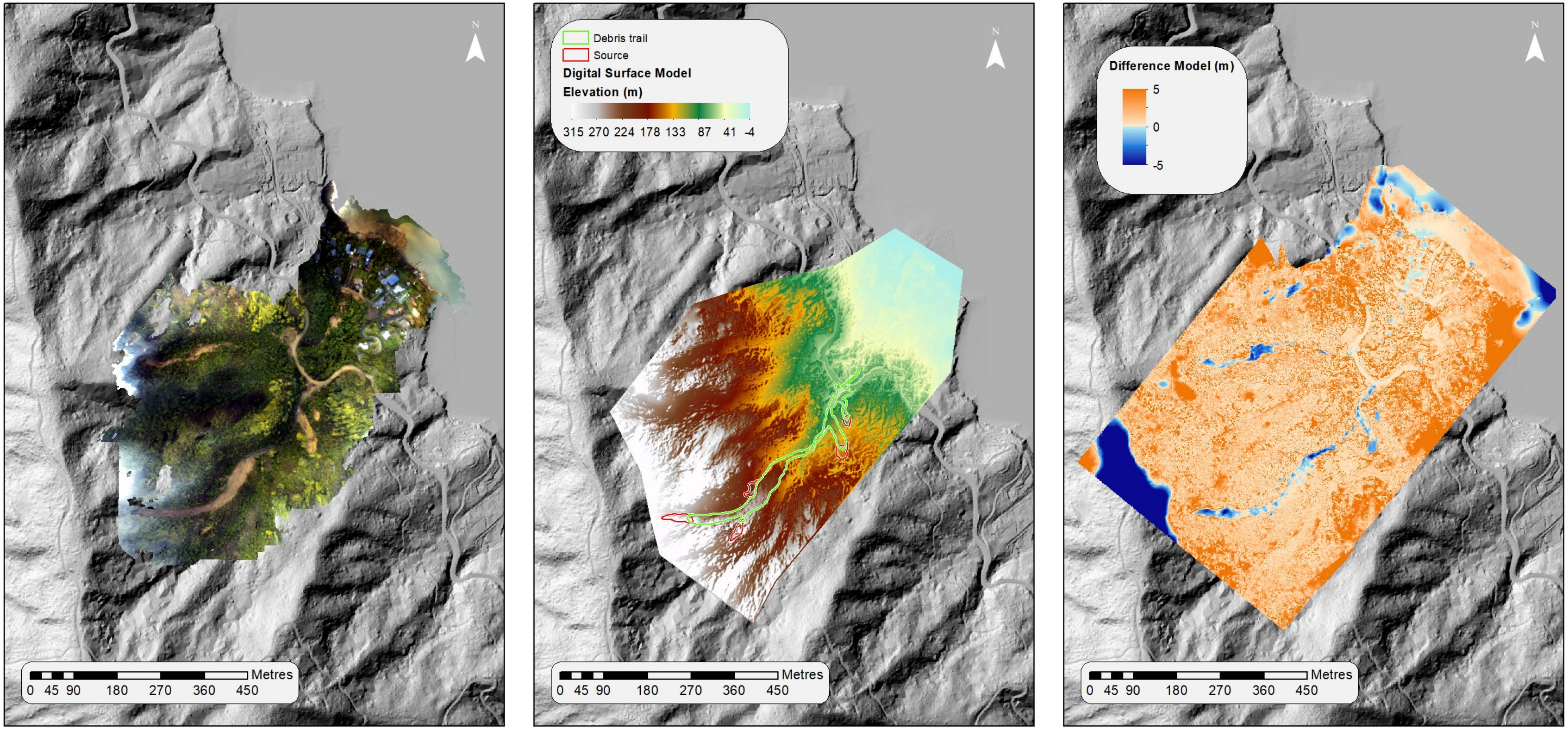


Figure A2.12 LSID 5: (Left) Orthophoto 30664x31765 pixels, 2.94 cm/pixel. (Centre) Digital Surface Model 16996x17884 pixels, 5.89 cm/pixel. (Right) Difference model.

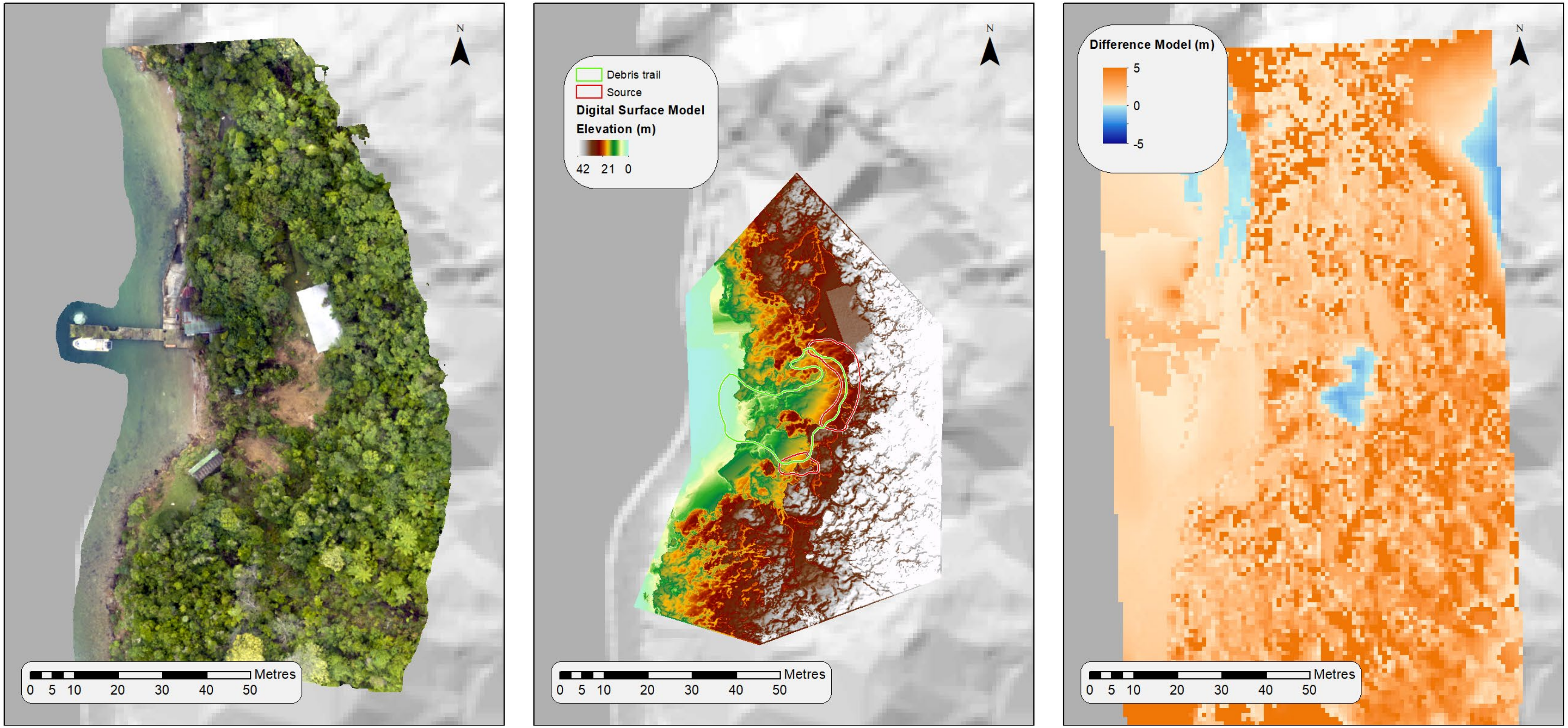


Figure A2.13 LSID 6: (Left) Orthophoto 6247x10267 pixels, 1.45 cm/pixel. (Centre) Digital Surface Model 3544x5692 pixels, 2.89 cm/pixel. (Right) Difference model.

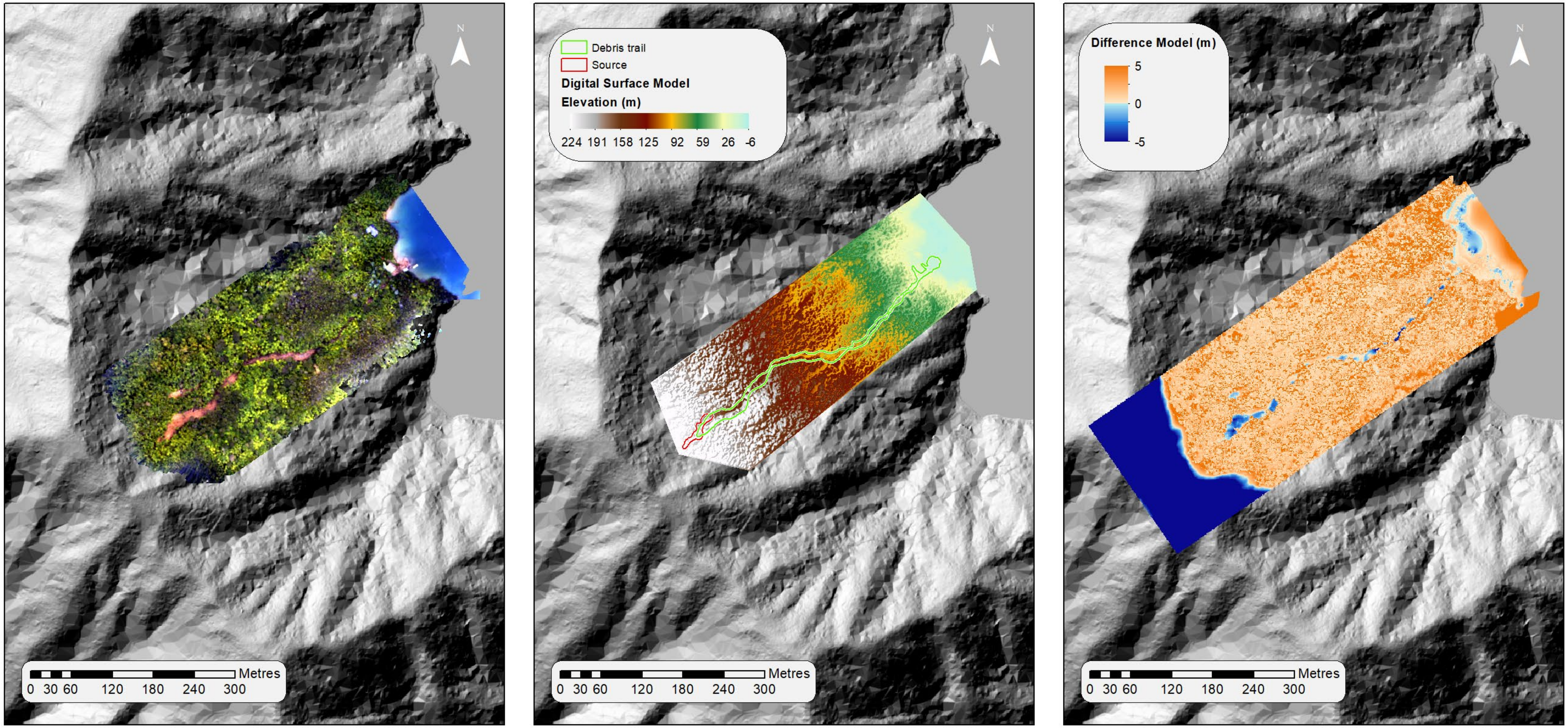


Figure A2.14 LSID 7: (Left) Orthophoto 29152x24653 pixels, 2.27 cm/pixel. (Centre) Digital Surface Model 32887x27231 pixels, 2.27 cm/pixel. (Right) Difference model.

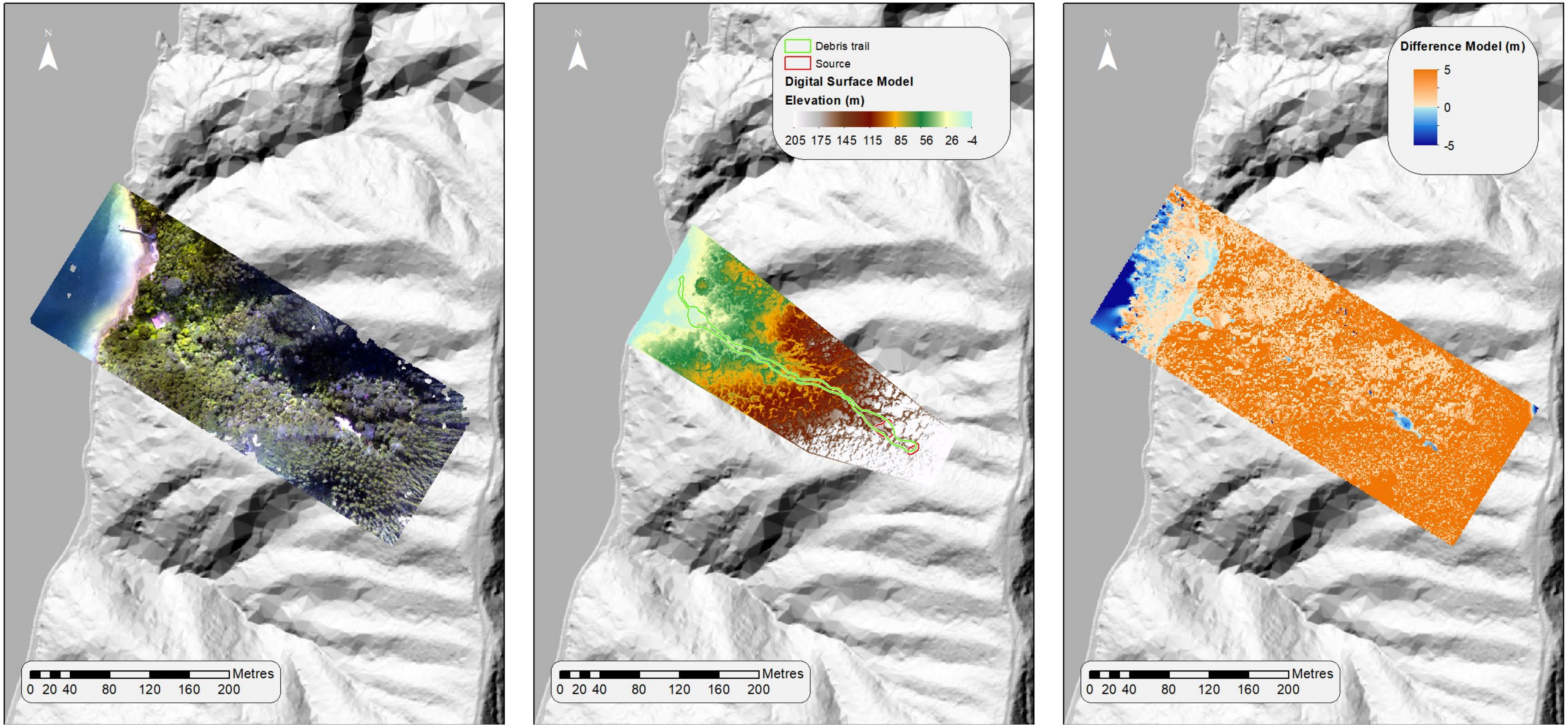


Figure A2.15 LSID 9: (Left) Orthophoto 20690x16554 pixels, 2.2 cm/pixel. (Centre) Digital Surface Model 10365x8279 pixels, 4.4 cm/pixel. (Right) Difference model.

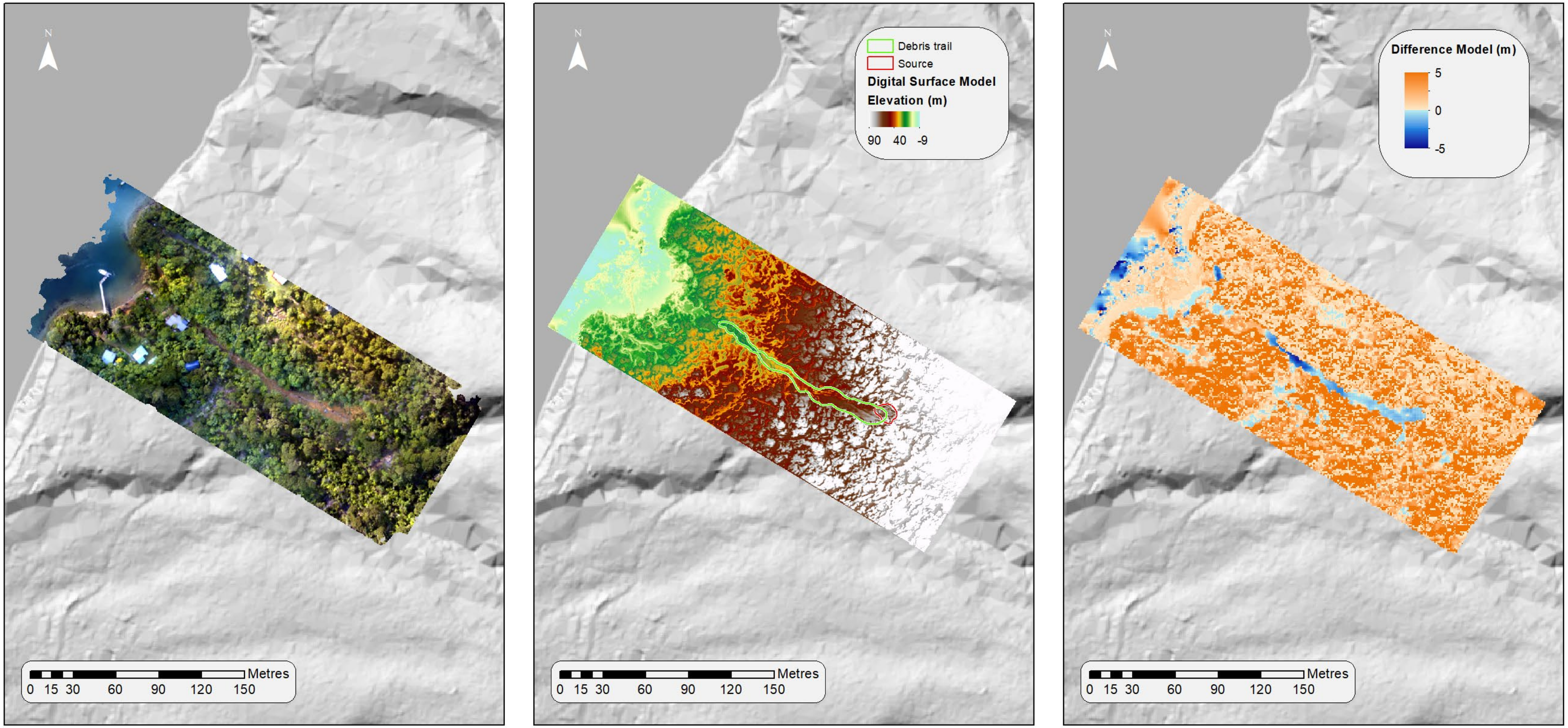


Figure A2.16 LSID 11: (Left) Orthophoto 16183x13483 pixels, 1.97 cm/pixel. (Centre) Digital Surface Model 8368x6784 pixels, 3.9 cm/pixel. (Right) Difference model.

APPENDIX 3 SURFACE DIFFERENCING METHODOLOGY

To difference the 2021 UAV photogrammetry models from the 2020 LiDAR Digital Elevation Models and Digital Terrain Models, the following procedure was completed:

1. Align UAV grids to the 2020 LiDAR grid for each landslide site.
2. Subtract 2020 LiDAR DEM from 2021 UAV DSMs → difference model 1.
3. Subtract 2020 LiDAR DSM from 2021 UAV DSMs → difference model 2.
4. Use con tool to split into erosion (negative change) and deposition (positive change) rasters.
5. Calculate the landslide source volume from the sum of erosion from difference models 1 and 2 within the mapped source polygon extent.
6. Calculate the landslide debris trail volume from the sum of deposition from difference models 1 and 2 within the mapped debris trail polygon extent.
7. Estimate the vegetation effect by summing the height of vegetation within the landslide source and debris trail polygons. The height of vegetation was determined by subtracting the 2020 DEM from the 2020 DSM.

APPENDIX 4 LANDSLIDE SURVEY DETAILS

Table A4.1 Table of landslide details I.

Landslide ID	Landslide Type	Source Visited	Source Area (m^2)	DT[1] Area (m^2)	Source Volume (m^3)	DT Volume (m^3)	DT Volume / Source Volume	H[2] (m)	L[3] (m)	H/L	Max Debris Height[4] (m)	Catchment Area (m^2)
1	Debris flow/flood	Y	675.4	2 345.9	7 479.3	9 684.8	1.30	84.5	245.5	0.36	1.5	73 926
2	Debris flow	N	852.9	4 590.5	1 523.3	6 977.6	4.58	146.8	460.5	0.33	-	140 696
3	Debris avalanche	Y	6 551.2	20 765.9	29 977.5	40 453.0	1.35	146.9	487.0	0.31	4.5	170 974
4	Debris flow/flood	N	-	-	-	-	-	-	-	-	-	-
5	Debris flow/flood	N	2 653.1	9 760.9	2 014.5	8 147.5	4.04	246.4	630.5	0.41	-	122 615
6	Debris slide/slump	Y	158.7	406.5	263.6	1 001.7	3.80	17.4	36.0	0.53	1.7	40 578
7	Debris flow	N	590.0	4 342.3	3 422.4	11 723.4	3.43	210.8	548.1	0.41	1.9	192 902
8	Debris flow	N	-	-	-	-	-	-	-	-	-	-
9	Debris flow	Y	312.3	1 955.1	2 037.6	15 511.0	7.61	150.3	326.7	0.50	0.5	83 120
10	Debris avalanche	N	-	-	-	-	-	-	-	-	-	-
11	Debris flow	Y	145.8	1 026.1	867.0	1 469.0	1.69	43.2	161.0	0.28	0	47 160

[1] DT = debris trail.

[2] H = height difference between landslide crown (top) and toe (bottom).

[3] L = landslide travel distance, calculated along the travel path of the debris.

[4] Maximum debris height on any building affected by the landslide, as measured along the back and side of each house impacted by the landslide.

Table A4.2 Table of landslide details II.

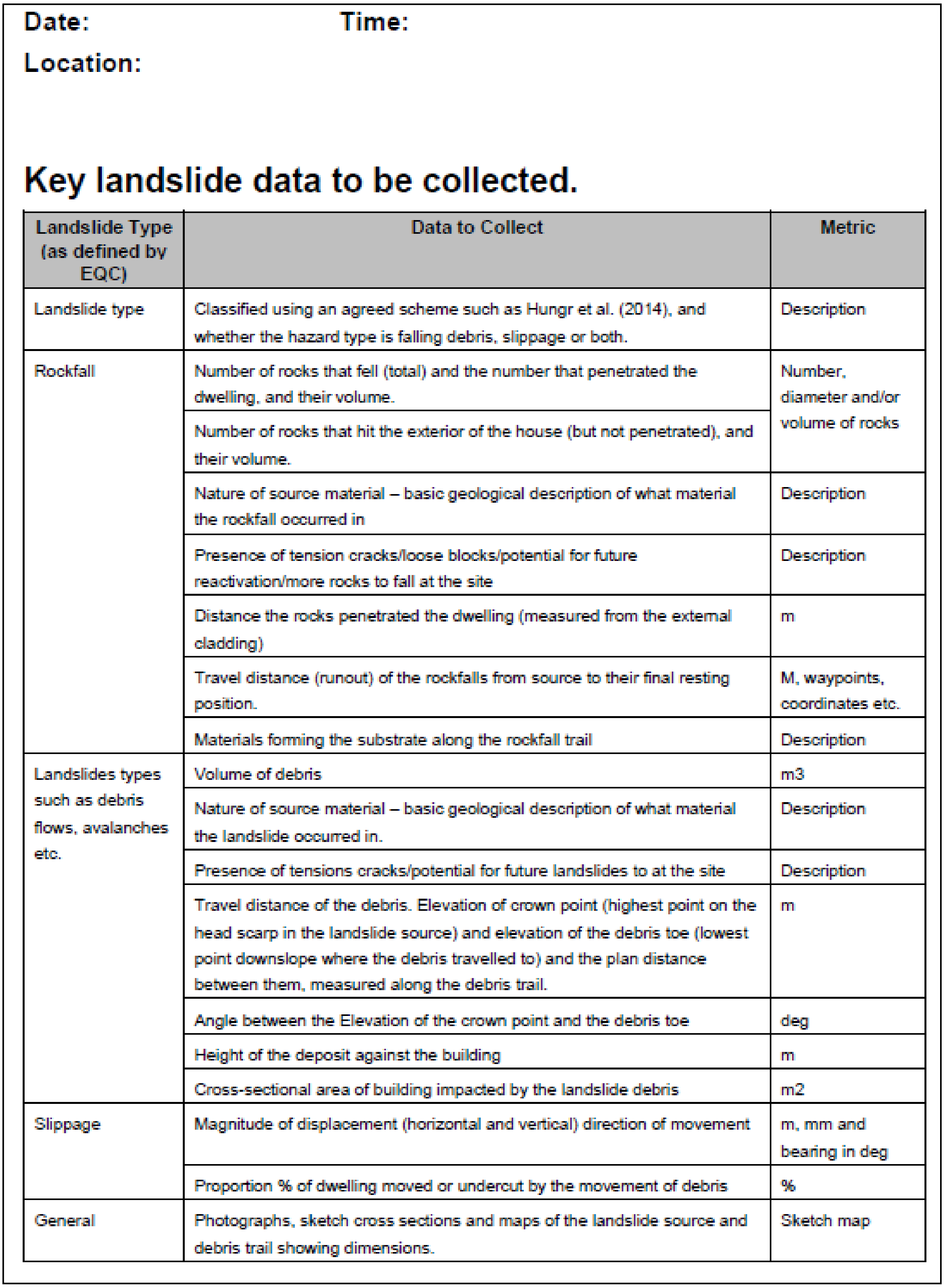
Landslide ID	Landslide Type	Future Landslide Potential	Source Material
1	Debris flow/flood	Some small tension cracks and small blocks above headscarp	Matrix-supported [1], saturated colluvium [2] on schist bedrock with silt, clay and clasts up to 60 cm, large woody debris > 10 m long
2	Debris flow	-	-
3	Debris avalanche	Source not fully evacuated	Matrix-supported, saturated colluvium with silt, clay and clasts >1.5 m and large woody debris
4	Debris flow/flood	-	-
5	Debris flow/flood	-	-
6	Debris slide/slump	Depression behind headscarp, minor blocks remaining	Matrix-supported, saturated colluvium on schist bedrock with clasts up to 50 cm
7	Debris flow	-	-
8	Debris flow	-	-
9	Debris flow	Some tension cracks above headscarp, overhanging surficial material (0.5 m deep)	Matrix-supported, saturated, sandy colluvium with organic layer and fines (largest clast 15 cm); on edge of pine plantation
10	Debris avalanche	-	-
11	Debris flow	Tension cracks above headscarp, 2-m-wide block hanging	Matrix-supported, saturated, silty colluvium with clasts up to 50 cm (greywacke)

[1] Matrix-supported material comprises >50% fine material (sand-size and smaller particles) as opposed to clast-supported material (>50% coarse material).

[2] Colluvium is any material, usually a range of fine sediments to rock blocks, that has moved downslope.

APPENDIX 5 BUILDING DAMAGE SURVEY DETAILS

A5.1 Chart to Determine Landslide Damage

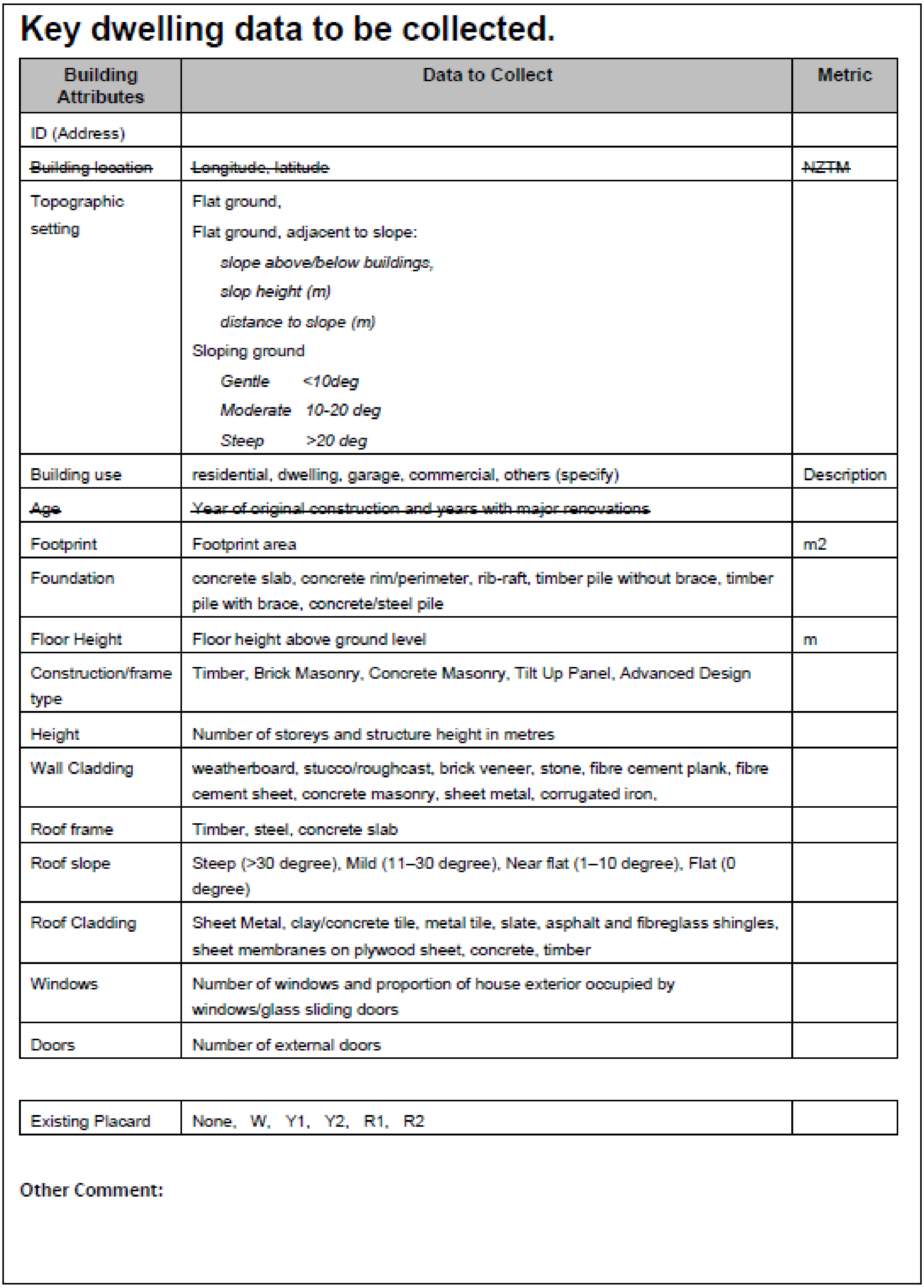


Date: **Time:**

Location:

Key landslide data to be collected.

Landslide Type (as defined by EQC)	Data to Collect	Metric
Landslide type	Classified using an agreed scheme such as Hungr et al. (2014), and whether the hazard type is falling debris, slippage or both.	Description
Rockfall	Number of rocks that fell (total) and the number that penetrated the dwelling, and their volume.	Number, diameter and/or volume of rocks
	Number of rocks that hit the exterior of the house (but not penetrated), and their volume.	
	Nature of source material – basic geological description of what material the rockfall occurred in	Description
	Presence of tension cracks/loose blocks/potential for future reactivation/more rocks to fall at the site	Description
	Distance the rocks penetrated the dwelling (measured from the external cladding)	m
	Travel distance (runout) of the rockfalls from source to their final resting position.	M, waypoints, coordinates etc.
	Materials forming the substrate along the rockfall trail	Description
Landslides types such as debris flows, avalanches etc.	Volume of debris	m3
	Nature of source material – basic geological description of what material the landslide occurred in.	Description
	Presence of tensions cracks/potential for future landslides to at the site	Description
	Travel distance of the debris. Elevation of crown point (highest point on the head scarp in the landslide source) and elevation of the debris toe (lowest point downslope where the debris travelled to) and the plan distance between them, measured along the debris trail.	m
	Angle between the Elevation of the crown point and the debris toe	deg
	Height of the deposit against the building	m
	Cross-sectional area of building impacted by the landslide debris	m2
Slippage	Magnitude of displacement (horizontal and vertical) direction of movement	m, mm and bearing in deg
	Proportion % of dwelling moved or undercut by the movement of debris	%
General	Photographs, sketch cross sections and maps of the landslide source and debris trail showing dimensions.	Sketch map

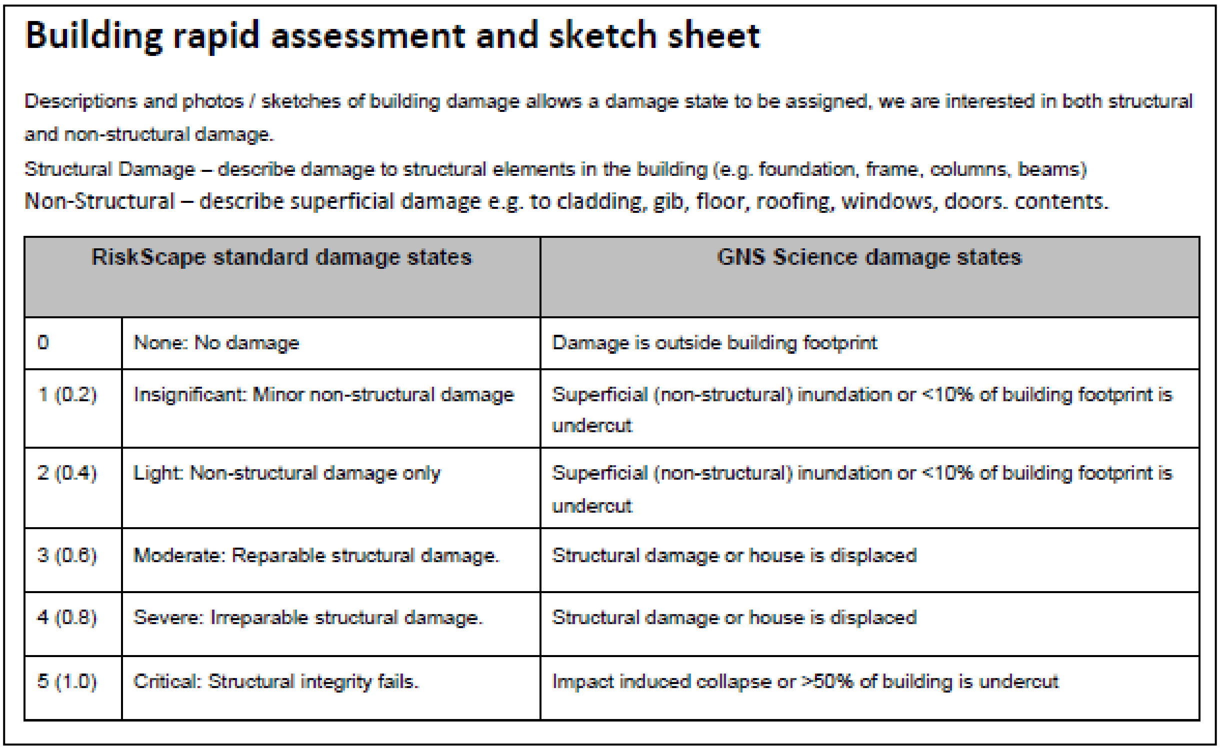


Key dwelling data to be collected.

Building Attributes	Data to Collect	Metric
ID (Address)		
~~Building location~~	~~Longitude, latitude~~	~~NZTM~~
Topographic setting	Flat ground, Flat ground, adjacent to slope: *slope above/below buildings,* *slop height (m)* *distance to slope (m)* Sloping ground *Gentle <10deg* *Moderate 10-20 deg* *Steep >20 deg*	
Building use	residential, dwelling, garage, commercial, others (specify)	Description
~~Age~~	~~Year of original construction and years with major renovations~~	
Footprint	Footprint area	m2
Foundation	concrete slab, concrete rim/perimeter, rib-raft, timber pile without brace, timber pile with brace, concrete/steel pile	
Floor Height	Floor height above ground level	m
Construction/frame type	Timber, Brick Masonry, Concrete Masonry, Tilt Up Panel, Advanced Design	
Height	Number of storeys and structure height in metres	
Wall Cladding	weatherboard, stucco/roughcast, brick veneer, stone, fibre cement plank, fibre cement sheet, concrete masonry, sheet metal, corrugated iron,	
Roof frame	Timber, steel, concrete slab	
Roof slope	Steep (>30 degree), Mild (11–30 degree), Near flat (1–10 degree), Flat (0 degree)	
Roof Cladding	Sheet Metal, clay/concrete tile, metal tile, slate, asphalt and fibreglass shingles, sheet membranes on plywood sheet, concrete, timber	
Windows	Number of windows and proportion of house exterior occupied by windows/glass sliding doors	
Doors	Number of external doors	

Existing Placard	None, W, Y1, Y2, R1, R2	

Other Comment:



Building rapid assessment and sketch sheet

Descriptions and photos / sketches of building damage allows a damage state to be assigned, we are interested in both structural and non-structural damage.

Structural Damage – describe damage to structural elements in the building (e.g. foundation, frame, columns, beams)

Non-Structural – describe superficial damage e.g. to cladding, gib, floor, roofing, windows, doors. contents.

RiskScape standard damage states		GNS Science damage states
0	None: No damage	Damage is outside building footprint
1 (0.2)	Insignificant: Minor non-structural damage	Superficial (non-structural) inundation or <10% of building footprint is undercut
2 (0.4)	Light: Non-structural damage only	Superficial (non-structural) inundation or <10% of building footprint is undercut
3 (0.6)	Moderate: Reparable structural damage.	Structural damage or house is displaced
4 (0.8)	Severe: Irreparable structural damage.	Structural damage or house is displaced
5 (1.0)	Critical: Structural integrity fails.	Impact induced collapse or >50% of building is undercut

A5.2 Building Attributes and Observed Impact from Field Survey

No.	Topographic Setting	Building Use	Age	Footprint (m^2)	Foundation	Floor Height (m)	Construction Type	Storey	Wall Cladding	Roof Frame	Roof Slope (°)	Roof Cladding	Landslide Type	Estimated Placard	Habitability	Estimated Damage	Damage Description
1	Flat ground, adjacent to slope	Residential	1990	172	Concrete slab	0.1	Timber	3	Weatherboard	Timber	Mild (11–30)	Asphalt and Fibreglass Singles	Debris flow/ flood	Y2	Unhabitable	DS3 (0.6); Moderate: Reparable structural damage	Landslide occurred on 17/7 (Sat) ~1300, residents not home. • 3 levels (GL: garage, L1: bedroom, lunch, kitchen, L2: bedroom). • GL: Concrete retaining wall, no damage (mud into the floor). • L1: Debris into the back of house (bedroom [over window height], toilet, laundry room [middle of door, ~80 cm]); mud everywhere in L1, in particular the back half. • L2: No visit but should be fine. • Debris flow from back hill side, overtopped retaining wall, reached L1 window height, tree branch penetrated into window of bedroom (L1).
2	Sloping ground (Gentle, <10°)	Residential	1940	110	Concrete/ steel pile	0.5	Timber	1	Weatherboard	Timber	Mild (11–30)	Sheet Metal	Debris flow/ flood	None	Habitable (Unoccupied)	DS1 (0.2); Insignificant: Minor non-structural damage	No sticker (but no obvious damage to the house, owners not home). • No obvious damage for main house, although mud went to back of house. • Debris around garden and driveway.
3	Flat ground	Residential	1940	110	Timber pile without brace	0.25	Timber	1	Weatherboard	Timber	Mild (11–30)	Sheet Metal	Debris flow/ flood	None	Unhabitable	DS2 (0.4); Light: Non-structural damage only	No sticker (no damage to house, except mud in every room); house next to main road, below the road surface; seems not occupied for a while?
4	Flat ground, adjacent to slope	Residential	2000	160	Concrete slab	0.25	Timber	1	Weatherboard	Timber	Mild (11–30)	Sheet Metal	Debris flow	None	Habitable (Occupied)	DS0 (0); None: No damage	Landslide blocked driveway, no damage/mud into the house, debris flow all the way down to the beach. • Took a week to clean the driveway debris.
5	Flat ground, adjacent to slope	Residential	2010	266	Concrete slab	0.25	Timber	2	Weatherboard	Timber	Mild (11–30)	Sheet Metal	Debris avalanche	R2	Unhabitable	DS5 (1.0); Critical: Structural integrity fails	2 levels (GL: garage, open carpark, L1: main house areas, hence L1 is larger and heavier than GL); occurred on 17/7 (Sat) ~0100, residents not home. • Debris took GL, building collapsed (pushed forward ~2.5 m, i.e. GL height) and L1 site on top of GL on the ground.
6	Sloping ground (Gentle, <10°)	Residential	2000	138	Concrete slab	0.25	Timber	2	Sheet Metal	Timber	Mild (11–30)	Sheet Metal	Debris avalanche	Y1	Habitable (Unoccupied)	DS0 (0); None: No damage	No obvious damage to building, restricted access due to risk from potential landslide and nearby damaged building, also road access to the house is compromised; residents were home, left home next morning.
7	Sloping ground (Gentle, <10°)	Residential	1960	124	Timber pile without brace	1	Timber	1	Weatherboard	Timber	Mild (11–30)	Sheet Metal	Debris avalanche	R2	Unhabitable	DS5 (1.0); Critical: Structural integrity fails	Building was destroyed by landslide and tree debris. • Roof nearly touching garden ground. • Building was in the way of landslide debris flow path (from hill source all the way down to beach).

No.	Topographic Setting	Building Use	Age	Footprint (m^2)	Foundation	Floor Height (m)	Construction Type	Storey	Wall Cladding	Roof Frame	Roof Slope (°)	Roof Cladding	Landslide Type	Estimated Placard	Habitability	Estimated Damage	Damage Description
8	Sloping ground (Moderate, 10–20°)	Residential	1970	71	Timber pile without brace	1.5	Timber	1	Weatherboard	Timber	Near-Flat (1–10)	Sheet Metal	Debris avalanche	R2	Unhabitable	DS4 (0.8); Severe: Irreparable structural damage	Debris flow, trees piled up and damaged the back part of house, pushed/rotated building from left to right a bit (separation shown in the deck). • Front part of building (lunch) looks good, no obvious damage. • Concrete block garage (boat shed) next to the house damaged (pushed by debris flow, wall cracked, block fallen). • Structural integrity compromised, no access to the house.
9	Sloping ground (Gentle, <10°)	Residential	1960	144	Timber pile without brace	0.25	Timber	1	Weatherboard	Timber	Near-Flat (1–10)	Sheet Metal	Debris flow/ flood	None	Habitable (Occupied)	DS1 (0.2); Insignificant: Minor non-structural damage	Debris from hill at the back of house, passed the road, went into property boundary; fortunately, the debris is lower than ground floor height, hence mud didn't go into the house. • Damage to the share driveway next to the house, also entrance of house.
10	Sloping ground (Gentle, <10°)	Residential	1950	120	Concrete slab	-	Timber	1	Fibre Cement Plank	Timber	Near-Flat (1–10)	Sheet Metal	Debris flow/ flood	Y2	Unhabitable	DS2 (0.4); Light: Non-structural damage only	Mud (30 cm higher than ground floor) went into the house and present in every room.
11	Sloping ground (Gentle, <10°)	Residential	1970	200	Timber pile without brace	-	Timber	1	Fibre Cement Plank	Timber	Near-Flat (1–10)	Sheet Metal	Debris flow/ flood	Y2	Unhabitable	DS2 (0.4); Light: Non-structural damage only	Yellow (to the sleepout, the main house is fine). • Mud went into the sleepout flat next to driveway. • No obvious damage to main house.
12	Sloping ground (Gentle, <10°)	Residential	1960	-	Concrete/ steel pile	0.4	Timber	1	Weatherboard	Timber	Near-Flat (1–10)	Sheet Metal	Debris flow/ flood	Y1	Habitable (Unoccupied)	DS1 (0.2); Insignificant: Minor non-structural damage	• Yellow-tagged building on the hill. • 1960? concrete piles (on a sloping 5° ground, but slope behind and in front of house), timber frame, weatherboard, sheet metal roof. • Ground floor height 40 cm. • (No obvious building from outside, just lose a bit of foundation).
13	Sloping ground (Steep, >20°)	Residential	1930	-	Concrete/ steel pile	1	Timber	1	Weatherboard	Timber	Mild (11–30)	Sheet Metal	Slippage	Y2	Unhabitable	DS3 (0.6); Moderate: Reparable structural damage	• Yellow-tagged building (sleepout) on the right-hand side, the main building was destroyed and cleaned (DS5). • 1930/40? concrete pile (on a sloping 30° ground), timber frame, timber board, sheet metal roof. • Current landslide hit left corner of sleepout, building was rotated, unstable? Evidence of previous landslide in the back of house but did not touch house. • DS3: Moderate: Reparable structural damage.

No.	Topographic Setting	Building Use	Age	Footprint (m^2)	Foundation	Floor Height (m)	Construction Type	Storey	Wall Cladding	Roof Frame	Roof Slope (°)	Roof Cladding	Landslide Type	Estimated Placard	Habitability	Estimated Damage	Damage Description
14	Sloping ground (Moderate, 10–20°)	Residential	1920	~250	Concrete/ steel pile	-	Timber	1	Weatherboard	Timber	Near-Flat (1–10)	Sheet Metal	Debris flow	Y2	Unhabitable	DS4 (0.8); Severe: Irreparable structural damage	Yellow-tagged: • Nobody home when landslide occurred, but family members were home the weekend prior to the event. • 1920/30? single-storey house, timber frame, weatherboard, sheet metal roof, stone foundation with rails on sloping ground (20°). • Building size (12.4 x 22 m). • Debris hit the left part of house, penetrated into two bedrooms on the right side, mud went from back to front, and from side to deck in the front. • No obvious movement of house.
15	Sloping ground (Steep, >20°)	Residential	2000	-	Timber pile without brace	-	Timber	1	Weatherboard	Timber	Near-Flat (1–10)	Sheet Metal	Debris flow	None	Habitable (Unoccupied)	DS0 (0); None: No damage	Landslide next to the house, no damage to houses.
16	Sloping ground (Gentle, <10°)	Residential	1940	~90	Concrete/ steel pile	-	Timber	1	Sheet Metal	Timber	Mild (11–30)	Sheet Metal	Debris flow	R2	Unhabitable	DS5 (1.0); Critical: Structural integrity fails	Red-tagged: • Debris hit the left side of house, took over foundation (timber frame on concrete piles) and rotated ~30°, stop on the sloping ground (i.e. can't stand inside damaged house). • 1940/50 timber frame, sheet metal roof/wall. • Two kids' sleepouts in the back of the house look okay.
17	Sloping ground (Gentle, <10°)	Residential	1990	-	Timber pile without brace	-	Timber	1	Weatherboard	Timber	Mild (11–30)	Sheet Metal	Debris avalanche	None	Habitable (Occupied)	DS0 (0); None: No damage	Severe landslide in the back of houses, no damage to houses.
18	Sloping ground (Steep, >20°)	Residential	1950	~190	Timber pile without brace	-	Timber	2	Weatherboard	Timber	Mild (11–30)	Sheet Metal	Debris flow	None	Habitable (Occupied)	DS2 (0.4); Light: Non-structural damage only	1950? timber house, sits on sloping ground (timber, concrete piles), with garage on the ground and main living areas on level 1. • House size 12 x 16 m. • Owners were not home that day, were notified by neighbours and came back for cleaning, still live in the house. • Debris went into back part of house (toilet, bathroom), tree penetrated back wall (80 cm diameter?), owners removed debris and have temporary repair to stop debris coming into the house. • Impact from debris was reduced by two garden sheds and trees in the back of house, the right part of house also had retaining wall protection.

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A5.3 Examples of Surveyed Buildings in Various Damage States

DS1 – Insignificant: Minor non-structural damage.

DS2 – Light: Non-structural damage only.

DS3 – Moderate: Reparable structural damage.

DS4 – Severe: Irreparable structural damage.

DS5 – Critical: Structural integrity fails.

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www.gns.cri.nz

Principal Location

1 Fairway Drive, Avalon
Lower Hutt 5010
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin 9054
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Private Bag 2000
Taupo 3352
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 30368
Lower Hutt 5040
New Zealand
T +64-4-570 1444
F +64-4-570 4657