Appendix B

Engineering Geological Report

Waitakere Coastal Communities Landslide Risk Assessment

Appendix B – Muriwai Engineering Geological Report

Auckland Council

15 May 2024

→ **The Power of Commitment**

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B1. Introduction

B1.1 Background

Two significant rainfall events affected the Waitakere area in late January and early February, resulting from the impacts of ex-tropical cyclones Hale and Gabrielle, respectively.

The Cyclone Gabrielle weather event of 14 February 2023 resulted in widespread catastrophic flooding and slope instability in the settlement of Muriwai where several debris avalanches (which included rocks and trees) occurred, some of which developed into saturated debris flows that resulted in damage to buildings and infrastructure. Two fatalities occurred due to impact of landslides on private dwellings. This tragic event was similar to a 1965 storm event that also claimed two lives.

Following the event, rapid building assessment of residential properties was undertaken in Muriwai, with some houses having access by owners restricted (a yellow placard – e.g., access in daylight hours only) and some for which no access was permitted (a red placard).

B1.2 Purpose of this report

GHD was engaged by Auckland Council (AC)[1] to carry out landslide risk assessments and to provide associated landslide risk management advice and geotechnical investigations in the Waitakere area, specifically for the residential areas of Muriwai, Piha and Karekare.

The purpose of this report is to present an engineering geological assessment of the Muriwai area to explain the context in which the damaging landslides of February 2023 occurred. This report is informed by remotely acquired topography data, historical information, community observations, geological mapping, subsurface geotechnical investigations and materials testing.

This report is an appendix to the overall GHD landslide risk report and should be read in conjunction with it, as well as the other associated appendices. The overall report contains additional information and synthesises the results of other appended assessments carried out by GHD (refer to Section B1.4).

B1.3 Scope

The agreed scope for this engineering geology assessment was as follows:

- Assemble GIS database information relating to topography, land use, geology and geohazards from publicly available sources, and that provided by AC. This has been used as a basis for presenting our findings.
- Undertake desktop and ground-based engineering geological mapping of the Muriwai settlement, focussing on characterisation of recent landslides and associated geological landforms.
- Present classification and indexing of recent large landslides within the Muriwai settlement.
- Present a summary of anecdotal evidence gathered from local community members that relates to geohazards, such as previous observations of ground instability or surface water flows.
- Review publicly available literature associated with Muriwai geology and landslide hazard.
- Provide an interpretation of the geology and geomorphology of Muriwai to understand possible future landslide distribution, characteristics and triggering mechanism(s).

Geotechnical ground investigations took place at the same time as the work described above and are presented in Appendix F.

[1] Under Contract CW198379, Master Services Agreement CCCS: CW74240 dated 7/09/2019

The focus of this study is limited to the assessment of the effects from 'large scale' landslide[2] hazards originating from the main escarpment located to the south-east of Muriwai because this is where damaging, fatality-causing landslides have historically originated. Smaller, more localised landslide hazards (on the scale of less than a property section wide or long) are not considered as they rarely lead to loss-of-life. The combination of numerous, small landslides would be considered if it were to result in a damaging debris flow.

Excluded from this report is consideration of the hazard relating to dwellings located along the crest of the main escarpment (i.e. the west side of Oaia Road) that could be undermined by regression of the escarpment during future landslide events. This is to be included in a separate future study.

This report: has been prepared by GHD for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in Section 1.2 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

B1.4 Report Structure

This report accompanies and informs numerous other assessments associated with the Muriwai landslides. A list of companion reports is presented in Table B1. A3 plans referred to in this report are listed in Table B2 and relevant additional images and data are presented in Appendices B-1, B-2, B-3 and B-4.

Table B1 Summary of accompanying Muriwai landslide risk assessment reports

Report Section	Description
Overall Report	Waitakere Coastal Communities Landslide Risk Assessment (Muriwai)
Appendix A	Figures
Appendix B	*Engineering Geological Report (this report)*
Appendix C	Slope Stability Assessment
Appendix D	RAMMS Debris Flow Analysis
Appendix E	Landslide Risk Assessment
Appendix F	Geotechnical Investigations Report

[2] In this report 'large scale' landslide hazards refers to landslides originating from the main escarpment that typically have a volume of more than about 50 m^3 with the potential to cause total or partial collapse of a dwelling.

Table B2 List of maps and images in Appendix A that are associated with this report.

Figure No.	Description
GENERAL SITE LAYOUT	
A101	STUDY AREA - OVERVIEW
ENGINEERING GEOLOGICAL PLANS	
A111	LEGEND
A112	OVERVIEW
A113 -A116	CLOSE-UP PLANS 1 - 4
CROSS SECTIONS	
A120	CROSS SECTION A-A’
A121	CROSS SECTION B-B’
A122	CROSS SECTION C-C’
A123	CROSS SECTION D-D’
A124	CROSS SECTION E-E’
GEOMORPHOLOGICAL LANDSLIDE ZONES	
A125	SLOPE RELIEF AND PROFILE COMPARISON PLAN
ELEVATION MODEL COMPARISON	
A126	ELEVATION COMPARISON BETWEEN 2016 AND 2023 LiDAR TOPOGRAPHIC SURVEYS
SLIP MECHANISM MODEL	
A127	2023 CYCLONE GABRIELLE LANDSLIDE MECHANISM MODEL - MURIWAI
A128	2023 CYCLONE GABRIELLE LANDSLIDE MECHANISM MODEL - PHOTO MARK-UP

B2. Methodology

B2.1 Data review

GHD received and sourced a variety pre-existing data to support the landslide risk assessments carried out within this report and supporting Appendices (Refer Section B1.4). A summary of this data including how and where it has been applied is given in Table B3 and discussed further below.

B2.1.1 Topographic data

Pre- and post-Cyclone Gabrielle topographic data from airborne LiDAR surveys were made available to GHD by AC and LINZ for this study for use in this report, the slope stability study (Appendix C) and RAMMS debris flow modelling (Appendix D). The spacing of data is 1 m, which is judged to be suitable for these purposes. We understand that the provided data had been processed to be 'bare earth', i.e. buildings and vegetation had been removed.

A comparison of pre- and post-Cyclone Gabrielle elevation data by GHD is presented in Figure A126 (see Appendix A). If the data were in spatial agreement, it is expected that areas that have not experienced any ground damage would have the same elevation. Landslides would exhibit a loss in elevation (i.e. a positive value in Figure A126) at the head of the feature and the debris flow runout would display a gain (i.e. a negative value in Figure A126). However, the comparison shows that, typically, areas in Muriwai not known to have experienced land damage exhibit a decrease in elevation post-Cyclone Gabrielle of up to 0.3 m and some localised undamaged areas of several square metres show a difference of more than 0.3 m. We therefore consider that data is accurate to ±0.3 m. We speculate that this may be due to one or more of the following reasons:

- The pre- and post-Cyclone Gabrielle datasets have been subject to different processing methods, particularly with respect to removal of vegetation.
- Different coverage areas and density of vegetation between 2016 and 2023.
- The 2023 landslides are typically unvegetated, allowing for accurate LiDAR.
- Erosion of the 2023 landslide surface between 14 February and 4 March 2023 (almost 3 weeks).

Further technical information regarding the data is described in Appendix B-5.

B2.1.2 Anecdotal community feedback

Anecdotal evidence from the occupants of an area can be a useful source of information to supplement and/or confirm formal evidence. The community contains many people who have resided in Muriwai for decades and some are multi-generational residents. GHD Engineering Geologists met with members of the public at the Muriwai Surf Club for two separate sessions on 28 May 2023 and then again on 2 and 3 September 2023.

Anecdotal testimony of residents was taken, with maps being referred to for identification of feature locations. Residents who were unable to participate with the in-person interviews were given the opportunity to email any information of importance to Auckland Council, which was forwarded to GHD. Appendix B-2 gives a generalised summary of the information, with some data appearing on Appendix A Figures A101 and A111-A116. We have not reproduced all names and addresses of contributors but have presented the common themes.

The September sessions were to provide clarification to residents by GHD and AC following the release of the draft version of this report and associated appended reports. There was a large response from the community from the draft release of this report, with additional observations and suggested amendments to the presented anecdotal information. The community's assistance was helpful, appreciated and used to help improve the report.

B2.1.3 Historical literature review

A review of published documents that relate to the landslide hazard in Muriwai is presented in Appendix B-3. Several of these discuss the 1965 and 2023 fatality-causing landslides. Several large flood events in the 1920s and 1930s are reported but, notably, no other damaging landslide events are described.

Table B3 Summary of received data

Data type	Owner	Detail	Quality and limitation	Application
Topographical survey	LINZ, Auckland Council (Appendix B-5 for details)	- 2016 LiDAR elevation model at 1 m point spacing from AC (pre-Cyclone Gabrielle) - 2016-2018 LiDAR elevation model at 1 m point spacing from LINZ (pre-Cyclone Gabrielle) - 2023 LiDAR elevation model at 1 m point spacing from AC (post-Cyclone Gabrielle)	- The two datasets were converted into Digital Terrain Models to derive topographical surfaces and contours - Figure A126 outlines a comparison between the two surfaces, showing the resolved volume difference. This indicates significant relative discrepancy, and potentially some distortion within each individual survey.	- The two datasets were converted into Digital Terrain Models to derive topographical surfaces and contours - The 2023 dataset has been used to inform GHD mapping in this report. - Pre and post-Cyclone Gabrielle data has been used to inform GHD slope stability (Appendix C) and RAMMS debris flow modelling (Appendix D).
Measured and estimated rainfall	Auckland Council (measured) and Met Service (estimated)	- Measured data from tipping bucket gauge 'TP-08' - Quantitative Precipitation Estimate (QPE) from Met Service	- Tipping bucket gauge TP-08 was damaged from flooding associated with the event and therefore did not provide continuous data over the course of the cyclone. - The QPE was generated from rainfall estimated off Met Services rain radar and used to derive rainfall accumulation and peak values. There is inherent uncertainty with this data given it is a quantitative derivative.	- Assessment of recurrence values assigned to the risk assessment (Appendix D). - General reference throughout this report and in comparison, with measured groundwater data (Appendix F)
Public bore records	Auckland Council legacy Consent Data	- Historical public bore records surrounding study area general vicinity - Records depth of bore, depth of measured groundwater level below ground level and date	- Unverified data, quality unknown	- General reference to support groundwater assessment (Section B4.3)
Historical aerial imagery	Aerial Photography: LINZ/ LGGA Satellite Imagery: Google	- Non continuous record since 1940, varying image scale - 1940 - 1975: Aerial photography - 2004 – 2023: Satellite imagery	- None-specific	- Illustrating past development and land use change across the study area and supporting discussions around overall geological characterisation pf he site. - Compiled in Appendix B-1 with relevant features marked.
Private property file data	Auckland Council	- Design and construction details of dwelling foundations and general property earthworks and stormwater/wastewater control	- Quality is variable dependant on completeness of data.	- Generally referred to in this report (Appendix B) to support understanding of any impact or otherwise from surface water drainage

B2.2 2023 – 2024 field investigations

B2.2.1 Geological field observations and measurements

Desktop and field-based mapping by GHD in 2023 and early 2024 collected discrete geological observational data over the whole study area. The mapping focused on definition of the extent and characterisation of the landslides. Associated engineering geological features such as springs and outcrops were also recorded. The data has been used to support the overall ground model interpretation and landslide characterisation and is reflected in Appendix A, Drawings A111 – 116, A120 – A127.

Landslides identified through the mapping process were catalogued in a register with common measurements included. This is attached as Appendix B-4.

The objective of the mapping was to:

- Confirm the location and extent of the February 2023 landslides.
- Record the observed exposed geology and geomorphological features.
- Inspect and assess pre-identified areas of geological interest (i.e. Edwin Mitchelson Track, geological outcrops, areas associated with anecdotal evidence).

The methodology included both desktop and field-based mapping:

1. Initial desktop mapping via QGIS and ArcMaps; identification and indexing of landslides using post-event topographical and photographic surveys; mapping of observable landforms and correlation with mapped geology.
    a. Initial site-based field mapping to ground truth the extent and nature of landslides (including their engineering geological properties), mapped geology extent and nature; assess geomorphological features and some man-made features (e.g. Edwin Mitchelson Track). This involved use of analogue (paper base maps) and digital techniques (ArcGIS FieldMaps) to collate GPS-tagged photographs and site notes;
2. Refinement and updating of final maps on desktop QGIS software following site-based data collection.
3. Further field mapping and updating of maps to include assessment of tension cracking adjacent to the escarpment crest (Oaia Road).

Site based mapping was carried out over the following dates:

- 24-26 May 2023: General mapping and classification of landslides, surficial geology and landforms surrounding escarpment
- 7 August 2023: Exploration for identification of tension cracking behind the escarpment crest.
- 30 Jan-15 Feb 2024: Further measurements of slope profile along escarpment crest.

B2.2.2 Subsurface geological investigations

Subsurface geotechnical investigations comprising nine rotary cored boreholes up to 80 metres deep, in-situ measurements, and installation of groundwater monitoring within constructed piezometer wells, were completed between 29th June and 17 August 2023. This was supported by a subsequent sampling and laboratory testing programme.

The investigations were intended to help develop an understanding of the ground conditions and groundwater regime in the vicinity of the site with particular emphasis on the material behind and below the escarpment. The data collected, including a detailed account of methodology of acquisition, calibration records and any reported error, is given in Appendix F (Geotechnical Investigations Report – Muriwai). The locations of the boreholes are shown on Figure A101 (Appendix A). Continuous telemetered groundwater monitoring of piezometers in six boreholes (BH-M01, M02, M03, M06, M07, M09) commenced from 19 October 2023.

B3. Study area description

B3.1 Nature and extent of the study area

Muriwai is situated on the west coast of Auckland at the north-western terminus of the Waitakere Ranges (see Figure B1 and Figure A101 (Appendix A). The site is defined by a near-continuous 1.5 km-long escarpment that is aligned to northeast – southwest. The escarpment face extends 80m vertically and is over 100 m above sea level at its crest. The town of Muriwai is built above and below it, including some properties directly at its base, and other directly on its crest. The landslides that have impacted Muriwai properties are predominantly located within this feature.

The crest of the escarpment is irregular along its length – some areas are inset further than others (Figure B1). Domain Crescent and Motutara Road are located within two larger inset areas and provide access to properties at the base of the escarpment. Oaia Road runs parallel to and setback from the crest and provides access to properties above the escarpment. Muriwai Beach, which comprises a long open coastline extending beyond the study area to the north, is accessed several hundred meters west of the escarpment, from which it is separated by sand dunes.

Current land use within and surrounding the site includes residential, isolated light commercial, recreational public land (beach frontage, regional park, and sand dunes), and private land (forestry and golf course).

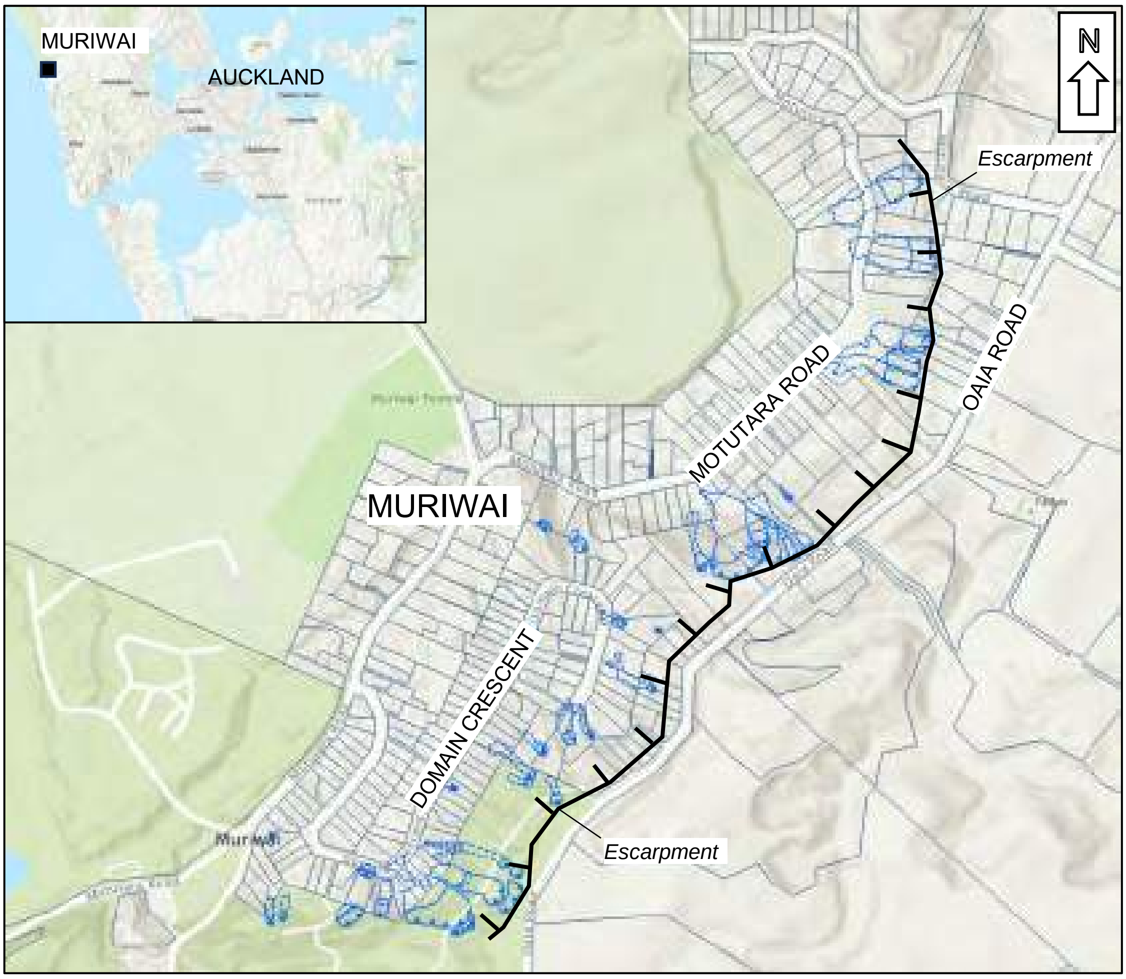


Figure B1 Muriwai location showing the February 2023 landslides mapped by GHD (blue lines)

B3.2 Study area geology

B3.2.1 Stratigraphy

Figure B2 shows the geological setting of the study area. Most of the site is locally underlain by Awhitu Sand Formation. The stratigraphy in the study area is summarised below and in Table B4.

Figure B2 *Excerpt from Hayward, B.W 1983: Sheet Q11, Waitakere. Geological Map if New Zealand 1:50,000. NZGS.*

3.2.1.1 Mitiwai Sand

'Modern beach and drifting sand, and fixed dune sand', Hayward, (1983). The sand black and minerally rich (iron and titanium). In relation to the study area, these sands make up the dune systems northwest of its boundary and impacted dwellings from the landslides.

3.2.1.2 Awhitu Sand

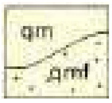
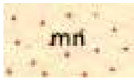
'Coarse sand, clayey, often limonitised (iron cemented), with minor tuff, lignite and siltstone', Hayward (1983). The limonite imparts some strength, making the material weak to extremely weak sandstone, when unweathered. The material weathers to a sandy soil at the surface. The country that Awhitu Sands underlies is typically rolling flat terrain except for where the escarpment is located which is comprised of this material. The sandstone varies from a massive to a bedded structure and is cross bedded at roughly metre scale.

3.2.1.3 Waitakere Group

Three formations of the Waitakere Group volcanic/volcaniclastic deposits uncomfortably underly the Awhitu Sands, in the proximity of the study area. Nihotipu, Waiatarua and Tirikohua Formations underlie the Awhitu sands and outcrop at the surface south of Domain Crescent on Waitea Road.

- **Nihotupu Formation**: volcaniclastic sandstone, thinly bedded at shallow angles, often with discrete layers of course angular volcanic conglomerate. Outcrops south of the study area. Deposited concurrently and interlain with Waiatarua Formation.
- **Waiatarua Formation**: submarine basalt flows and pillow lavas. Columnar jointing common. Locally weathers to clay near the surface.
- **Tirikohua Formation**: volcaniclastic sandstone, bedded at shallow angles. Generally comprising finer grained material than Nihotupu Formation.

Table B4 Study area geological stratigraphy

GNS Group	GNS Formation	GNS symbol	Geological age (absolute)
Kaihu Group	**Mitiwai Sand, fixed dunes (qmf)**		Holocene, <10 Kya
	Awhitu Sand (qs)		Pleistocene, <2 Mya
	Regional unconformity		
Waitakere Group	**Tirikoha Formation (mt)**		Late Miocene, ~ 5 Mya
	Waiatarua Formation (mw)		Miocene, ~23 – 5 Mya
	Nihotupu Formation (mn)		Miocene, ~23 – 5 Mya

Note: Stratigraphy as per Hayward, (1983), GNS 1:50,000 Map, Sheet Q11 Waitakere

B3.2.2 History and structure

From the late Miocene to Pleistocene, the geological history of the study area is broadly summarised as being subject to repeating cycle of deposition, erosion, uplift and further down-wearing of the Waitakere Group volcanic deposits (Hayward, 1979). From the Pleistocene onwards, the Awhitu Sand Formation has been deposited unconformably on-top of an erosional surface of the Waitakere Group (Nihotupu and Waiatura Formations at the study area) and as a result experienced similar uplift and down-wearing cycles. The uplift occurred on a series of faults that primarily strike Northeast and have formed 'blocks' of land that are upthrown and downthrown relative to each other (Hayward, 1976). This process has also resulted in shallow (10-15°) dip to the northeast along the unconformity, within the 'Maori Bay Block', as mapped immediately south of the study area (Figure B2).

Tirikohua Formation locally outcrops in the coastal cliff line southwest of the study area and is bounded by a fault that is mapped to continue to the northeast before losing its surface exposure at the southern extent of the study area (i.e. at Domain Crescent). It is unclear whether this fault continues to the northeast along the base of the escarpment.

B3.3 Surface characteristics

B3.3.1 Surface features

The top of the escarpment has a prominent scalloped nature, as shown in Figure B1, and combined with the presence of the irregular (hummocky) benches occupied by Motutara Road and Domain Crescent below the escarpment suggests that study area may have been subject to large-scale land sliding in the past. The mapping and drilling described in Section B2.2 were undertaken partly to investigate this possibility.

B3.3.2 Surface water catchments

There are approximately ten small catchments within the vicinity of the Muriwai escarpment and there are numerous surface water flow paths within these (see Figure B3). The surface water west of the escarpment flows to the west and the surface water at Oaia Road and surrounding properties flows to the northeast.

GHD (2023[1]) assessed the stormwater discharge from 35 properties between Oaia Road and the escarpment edge and demonstrated that the discharge from private properties drains towards Oaia Road and that the public stormwater system on Oaia Road is adequately sized and conveys flows away from the escarpment.

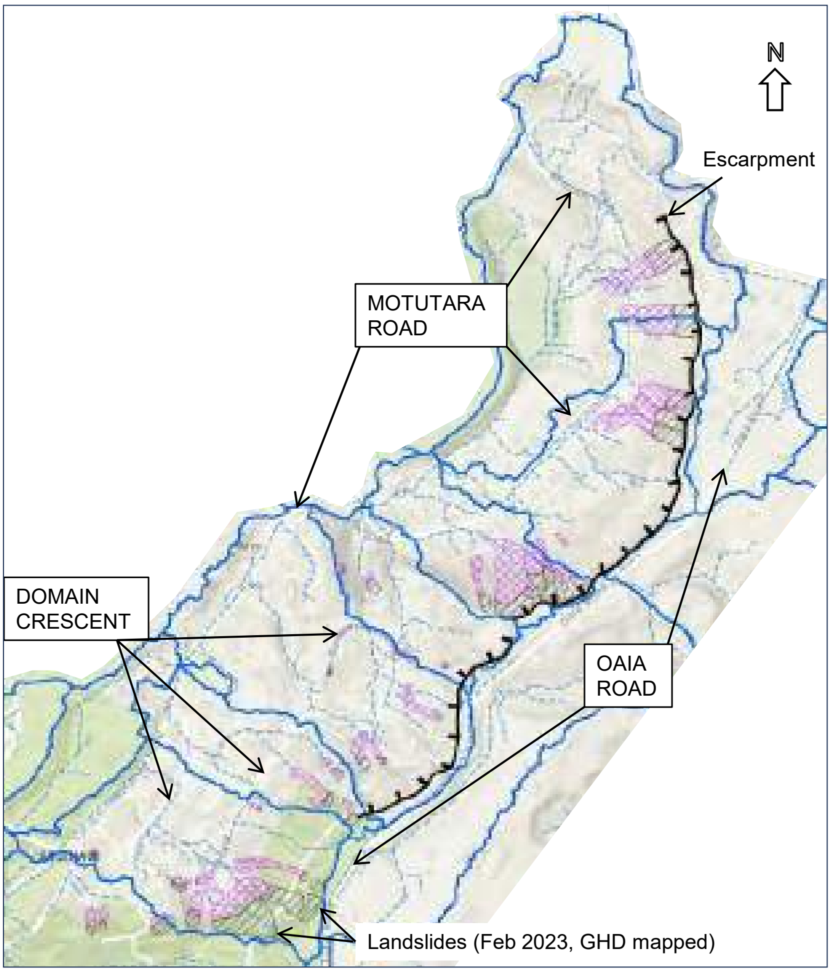


Figure B3 ***Water catchments in Muriwai. Solid blue lines are individual catchments and thin blue dashed lines are nominal surface water flow paths. Defined by GHD using LINZ topographic data.***

B3.4 Historical land-use change

Appendix B-1 presents available historical aerial photographs and satellite imagery of the Muriwai area from 1940 through to 2023. A summary of the known land use and vegetation change since the early 1900s is given in Table B5.

Table B5 Land use change from early 1900s to the present day

Time period	Commentary
Early 1900s	- Refer to Figure B4 (view north from Edwin Mitchelson house) - Residential development began in the early 1900s with isolated dwellings accessed by Oaia Road and Edwin Mitchelson Track - Coastal/dune systems along Muriwai beach undeveloped and possibly lower in elevation
1940	- Motutara Road constructed, associated with more residential development and several community buildings near beach. - Escarpment is covered in low density scrub and medium sized vegetation. Some areas below escarpment have been recently cleared. Coastal sand dunes are unvegetated. - Exposed soil/rock noted near the crest and off leading ridgelines. - Surrounding countryside mainly cleared and predominantly agricultural land use.
1950 – 1975	- Domain Crescent, Waitea Road constructed, later followed by Coast Road (1975), associated with continual residential and commercial infill in these areas. Many sections still bare or utility structures only. - Muriwai Golf course constructed and local earthworks / contouring of land apparent. - Stormwater reservoir to the west of Motutara Road now constructed. - Pine plantation established northwest of Motutara Road, cleared and regrown.
1975 – present day	- Continual infilling of residential development both below and above escarpment - Wilding pine and native vegetation gradually increasing across escarpment to present day density.

Figure B4 *Early 1900s (unspecified), approximate location of present-day Edwin Michelson Track/Oaia Road, looking due North over Muriwai Beach. Source: Supplied by Auckland Council, 2023, Edwin Mitchelson House*

B3.5 1965 Landslide event

Two parallel landslides occurred on Domain Crescent on 27 and 28 August 1965, destroying two dwellings and killing two people. These landslides followed two days of unusually heavy rain, with a nearby gauge recording 95 mm on August 25 to 26, plus 45 mm in the 12 hours preceding the landslide that occurred on 27 August 1965 (Hayward, 1965). Elsewhere between 190 mm (Manukau Heads) and 220 mm (Whenuapai) was recorded over the 3-day period. The two landslides were reported as fast-travelling mud slides by witnesses. Many additional smaller landslides occurred over the wider area for several days after the rain event (Wright, 1996). The headscarp of the two larger landslides was located directly below Edwin Michelson Track. Various reports at the time suggested they were triggered by excessive surface water being diverted off the track resulting from blocked table drains (Hayward, 2022). Wright (1966) observed that for days after the events water seeped out of the Awhitu Sand about midway up the landslide paths. Hayward (2022) concluded that the landslides were likely triggered by a combination of the surface water flows and the groundwater springs.

The two separate debris paths coalesced near the bottom of the escarpment and flowed across Domain Crescent (Figure B5 and Figure B6). Both the destroyed dwellings were located on the uphill side of the road and were translated with the debris flow.

Five dwellings have since been constructed at the site of the 1965 landslides. A series of new landslides occurred at the same location resulting from the 2023 ex-tropical cyclones.

Figure B5 Mapped extent of 1965 Landslides (after Wright 1966)

Figure B6 View from Domain Crescent of 1965 landslides and destroyed dwellings (after Wright 1966)

B3.6 Overview of February 2023 landslides

The February 2023 landslides occurred along the Muriwai Escarpment within Awhitu Formation sand and silt, above the Domain Cresent and Motutara Road benches, and from several leading ridgelines between. The locations of all recorded landslides are given in Figure A101 (see Appendix A). Examples of the damage associated with the runout are given in Figure B7 and Figure B8. Key details of the event are summarised as:

- Most landslides originated near the crest of the escarpment on the evening of the 14th February 2023 (peak rainfall intensity), travelling down the face and terminating at or close to the base. Most landslides were greater than 50 m^3 of material released and often entrained large amounts of vegetation, including trees.
- The material was saturated and flowed at significant speed, giving little to no warning.
- Significant damage and destruction (including complete collapse) of impacted residential structures occurred, contributing to two fatalities. In addition:
  - o Some properties above the landslides (accessed from Oaia Road) were partially undermined from the loss of material.

- o Various damage to non-residential structures also occurred (commercial buildings; AC property; walking tracks)
- On-going erosion after the event resulted in the repeated blocking of public table drains in road corridors.
- Many new groundwater springs were observed to be emitting constant flow after the event.

Figure B7 ***Entrained vegetation and sand/silt comprising the overall 'colluvial debris', GHD 2023. Debris resulting from Landslides M-LS07,08,09.***

Figure B8 ***Example of significant destruction of dwelling, associated with landslide debris runout, GHD 2023. Debris resulting from Landslides M-LS12.***

B4. Engineering geological interpretation

This section of the report explains the development of the engineering geological model of the site area from analysis of the available geological, geomorphological, groundwater and surface water data.

B4.1 Geological units

Engineering geological units were developed from the GNS mapped geology (Table B4) and the site investigation data (Appendix F) to support the ground interpretation and landslide assessments of the study area. The information is presented as follows:

- Table B6 summarises the geological unit characteristics and defining features.
- Illustrations of examples of the units as recovered in borehole core and/or observed in outcrop are given in photo figures below the table.
- Interpretation of the surface distribution of the units is given on the Engineering Geological Maps (Appendix A, Figures A111 – A116).
- Interpretation of the sub-surface distribution of the units is given in the Engineering Geological Cross Sections (Appendix A, Figures A120 - 124).

B4.2 Geomorphology

The study area has been divided geomorphologically into six landslide ‘zones’ based on the surface topography, February 2023 landslide characteristics and general geomorphology. The purpose of this is to differentiate areas according to their susceptibility of large-scale landsliding. The geomorphological zones are shown on the attached engineering geological maps (Appendix A, Figures A111 – A116) and the basis for the zoning and the zone characteristics are described in Section B6.3.

Table B6 Engineering geological units

GNS Formation	Engineering geological unit	General description / comments	In-situ strength characterises	Occurrence across study area	Example photo figures
N/A	**Recent Colluvium (2023)**	- Orange to pale yellow, uncemented and unconsolidated sand, varying level of silt intermixed. Usually entrained with surficial vegetation debris and topsoil. - Still consolidated/cemented blocks near source (headscarp) which are partially broken down - No discernible structure or internal fabric - Easily eroded / dispersed by surface water - Sourced from Less Cemented Sand unit	- No measurable strength - Inferred as very loose, with friction angle of less than 10°.	Within mapped landslide, usually collected at the base of the escarpment along Domain Crescent and Motutara Road. Some material still preserved on escarpment face.	-Figure B7 -Figure B8 -Figure B9
	Fill Deposits	- Orange, brown clayey silt, mixed with topsoil - Less than 1 m thick where encountered	- Single shear vane value > 100 kPa	Encountered locally within single borehole (BH-M02) however inferred to be present across study area in discrete and small volumes (<50 m^3) to support residential, building platforms, localised road fill	-Figure B10
	Ancient Colluvial & Alluvial Deposits	- Chaotic' texture with irregular shaped clasts of silty and clayey material - Varying degrees of organic material - Often significant (more than 1 m) inclusions of 'intact' Awhitu formation sand, cross bedded - Sharp and irregular boundaries between varying textures/types of material - Within BH-M06, potentially contains alluvial materials as well as colluvial sourced material	- Variable, generally characterised by: - SPT 'N' value 0 to <20	Encountered to varying depths within boreholes: - BH-M05, BH-M07, BH-M08, up to 7.5mbgl. - BH-M06, up to 38 mbgl Lateral extent between boreholes poorly constrained.	-Figure B11 -Figure B12
Awhitu Sand Formation (qs)	**AS: Less Cemented Sands** ***Includes discrete layers of:*** ***- ASf: Organic Soil / Peat*** ***- ASf: Silt/ Clay***	- Variable coloured and weathered, generally orange, light yellow, or cream white at surface, and orange to grey below surface - Uniformly graded medium to coarse sand - Some cement (evident by in-situ density) although often recovered as unconsolidated and dilated in core - Discrete layers of limonitic material - Crossbedding common at a sub-metre scale with laminated layers 0.1 m thick, with no visible preferred orientation. - Bedded to massive, beds 1-2 m thick separated by thinner (<1.0 m) layers of finer grained material. In outcrop, beds display near horizontal, slight northward dip. Non-continuous. - Jointing vertical and tight, develops moderately sized blocks <1m3 near crest Escarpment - Occasional occurrences of thin layers/lenses (<1.0 m thick) of finer grained silt, and peat - Prone to erosion ('dispersibility') and possible tunnel gully erosion based on the results of Pinhole and crumb testing results (Appendix F, Section F4.5). Note – no direct evidence of tunnel gully erosion has been observed during GHD site investigations, or within previously documented studies.	- SPT 'N' value 0 – 20, generally unchanging with depth, some variability with more cemented sand layers. - UCS <1 MPa - Peat and silt/clay layers unmeasured, inferred: -SPT 'N' value = <10 -Vane Shar strength = <50kPa	- Surficial deposit over majority of study area, exposed within the slip face of most recent landslides. - Generally encountered to 20-30 m bgl before transitioning into cemented sands/candstone (below) - Bedding and crossbedding observed in outcrop in many landslide source areas - Layers of silt and clay observed in outcrop and often extending up to 100 m laterally at surface, 1.0 m thick - Peat layers rarely encountered and not traceable laterally.	-Figure B13 (cross bedding -Figure B14 (less cemented sand) -Figure B15 (interbedded sand and silt layers) -Figure B16 (silt/clay layer) -Figure B17 (peat/organic soil)
	AS: Cemented Sand / Very weak Sandstone ***Includes discrete layers of:*** ***- ASf: Organic Soil / Peat*** ***- ASf: Silt/ Clay***	- Generally dark orange, - Variably weathered (slightly to moderate), extremely weak to weak, iron cemented Sandstone. Massive to bedded. - Presence of more cement than the overlying less cemented material is inferred to be responsible for the increase in in-situ strength. - Uniform (coarse) grained sand clasts - Similar but better preserved fabric as overlying less cemented material: - Cross bedding <1m scale, horizontally bedded (interbedded with finer grained material) - Irregular occurrences of limonite layers	- SPT 'N' Value = 50+ - UCS >1 MPa, to >2 MPa	Not encountered in outcrop / at surface, generally 20-30 m and deeper below local ground level	Figure B18
Nihotupu Formation (mn)	**N: Residual Silty Clay**	- Dark red and brown, very stiff clayey silt and gravelly silt. - Irregular limonite staining - Relic rock texture visible	- Vane shear strength = >100 kPa - SPT 'N' Value = 17-22	Encountered south of study area at surface, in outcrop (Awatere Road). Within study area, encountered in BH-M04 from surface (below road fill).	Figure B19

***<u>Note:</u>* Mitiwai Sand Formation** *is referred to in Section B2.2.1.1 and included within Appendix A figures for general reference, where indicated by Hayward (1983) mapping. It has not been assessed from an engineering geological perspective as it is not encountered within the study area at the surface / sub-surface. It is not considered relevant to the observed landslides that have occurred on the escarpment face.*

Figure B9 ***Example of engineering geological unit '2023 Recent Colluvium'. Medium grained sand, unconsolidated, spread out thinly across existing surfaces.***

Figure B10 ***'Fill Deposits' soil recovered in BH - M02: 0.0-1.5 mbgl***

Figure B11 ***'Ancient Colluvial/Alluvial' soils recovered from BH-M07: 3.65-5.34 mbgl***

Figure B12 *Example of in-situ 'blocks' of cross-bedded Awhitu Formation within Ancient Colluvial/Alluvial soils, from BH-M06: 36.45-38.2 mbgl*

Figure B13 *Outcrop of Awhitu Sand Formation - Less Cemented Sands, cross bedding evident (left). Exposed within 2023 landslide, Domain Crescent.*

Figure B14 *Example of Awhitu Formation Less Cemented Sands, weakly consolidated material from BH-M02, 11.6-14.7 mbgl*

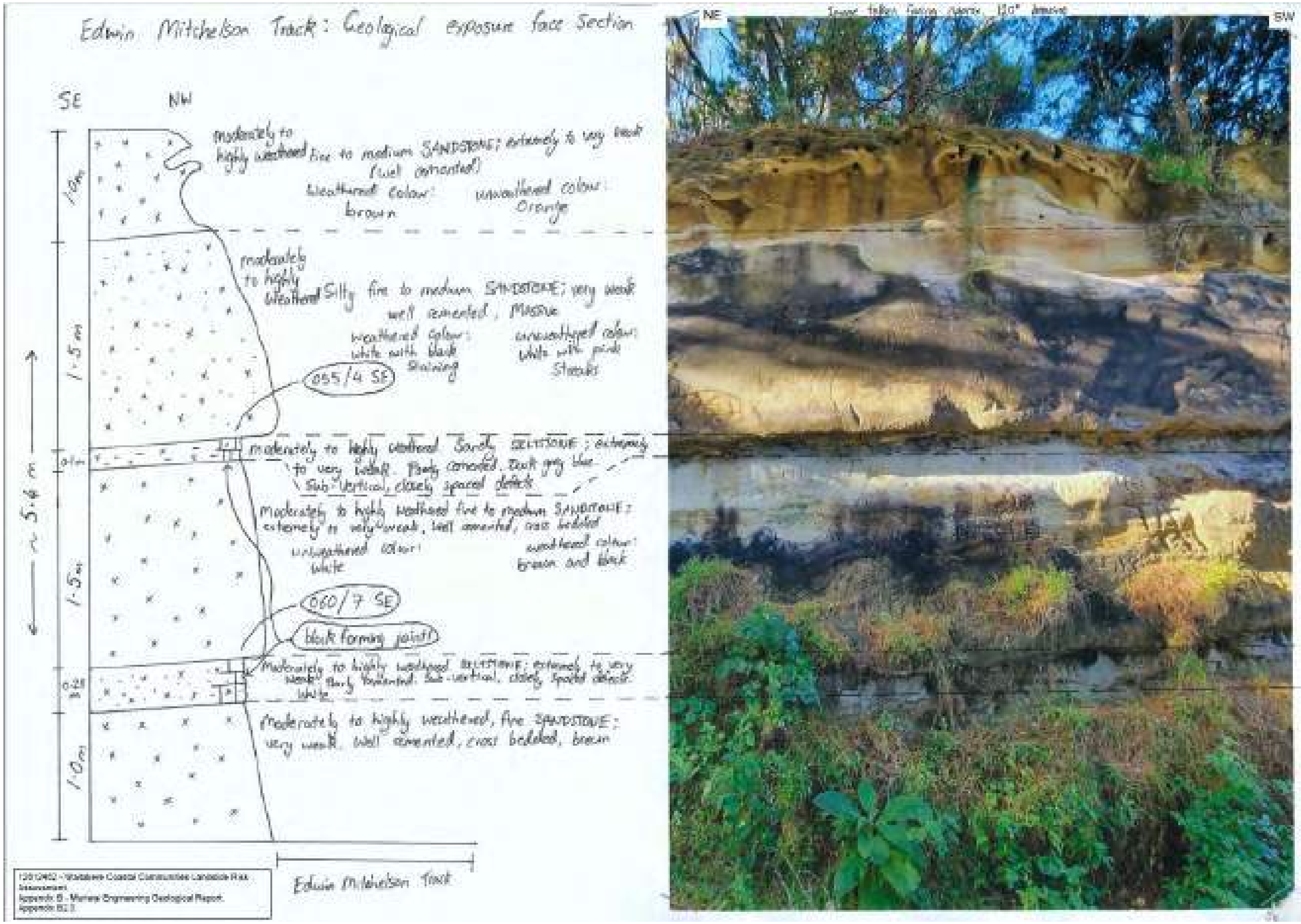


Figure B15 *Face log of Awhitu Formation Less Cemented Sands preserving rock fabric and structure, Edwin Mitchelson Track cut slope. Refer Figure A116 for specific location (marked).*

Figure B16 ***Outcrop of Awhitu Formation – Less Cemented Sands, layer of finer grained material (silt, clay). Approximate thickness 1 m.***

Figure B17 ***Example of layer of peat/organic soil within Awhitu Formation Less Cemented and Cemented Sandstones, from BH-M02, between 7.95 8.75 m bgl.***

Figure B18 ***Example of Awhitu Formation Cemented very weak Sandstone, oxidised, from BH-M02 36.65-37.5 mbgl***

Figure B19 Example of Nihotupu Formation Residual Silt and Clay, from BH-M04 3.95-5.90 mbgl

B4.3 Groundwater

B4.3.1 Data

Table B7 summarises the available groundwater data and our assessment of this data.

Table B7 Summary of groundwater data reviewed and observations

Data	Comment	Example / reference
Surface seeps/springs	Springs have been observed and mapped across the escarpment (Figure A112-116). Where the source of seepage was observed directly it was commonly located above finer grained silt/clay beds and more oxidised/cemented layers (limonite).	Figure B20 Figure B21
Variable head permeability testing	Hydraulic conductivity values measured within BH-M01, M02, M06 and M07 (E-08 to E-09) are considered typical for the material that their respective screens are constructed within (massive sandstone, M01, M02, M07) and silt/clay soil (M06).	Appendix F, Table F6
On-going groundwater level monitoring	Continuous groundwater level monitoring established in six piezometers since 19 October 2023 (BH-M01, M02, M03, M06, M07, M09). - Refer discussion below, assumed error within BH-M01 and M09 - BH-M03 has been dry since shortly after installation. - Generally little to no connection observed between recorded rainfall and groundwater level, except for: -- BH-M06: positive correlation when peak daily rainfall exceeds approximately 12 mm/day. Fluctuation in groundwater level relatively short, generally +/- 2 mbgl for 1-2 days following peak rainfall. -- BH-M07: weak correlation when peak daily rainfall exceeds approximately 15mm/day, corresponding groundwater level fluctuation of less than 0.5 m, with very gradual return to baseline level (2-3 weeks). - Generally stable / unchanging monthly average values, no seasonal variation observed.	Section F3.3.3 Appendix F5 (groundwater vs rainfall graphs)

Data	Comment	Example / reference
Electronic dip-tape measurements	Sporadic measurements to calibrate telemetered data. Minor variance in measurements, considered insignificant to trend observed in telemetry.	Appendix F, Table F5
Legacy bore records – groundwater levels (AC)	3 bores installed surrounding the project area. #21261 and #22794 record significantly deeper groundwater levels (120-129 mRL than adjacent GHD piezometer BH-M01 (approximately 80 m vertical RL difference). GWL at BH-M03 is unclear given well is dry. Recorded geology at screen suggests bore is socketed into underlying Waitakere Group deposits.	Figure B22

Data limitations

- Piezometer BH-M01 data is considered invalid (erroneous) given both the 'erratic' nature of day to day changes in recorded groundwater level and the two significant sudden changes of approximately +/- 8 m vertically over 24 hr time periods that are uncorrelated to measured rainfall. The telemetry unit and data have been inspected for any obvious physical or recording errors/damage, however none were revealed.
- Piezometer BH0M09 data is considered as potentially invalid given the recorded groundwater level is physically unchanged over the recorded interval expect for one brief (<24 hr) change in late November before returning to the constant reading approximately 7.6 mbgl.

Figure B20 Groundwater seepage above highly oxidised (limonite) layer within Awhitu Formation 'less cemented' sand

Figure B21 *Groundwater spring emitting above silt/clay bed within Awhitu Formation 'less cemented' sand.*

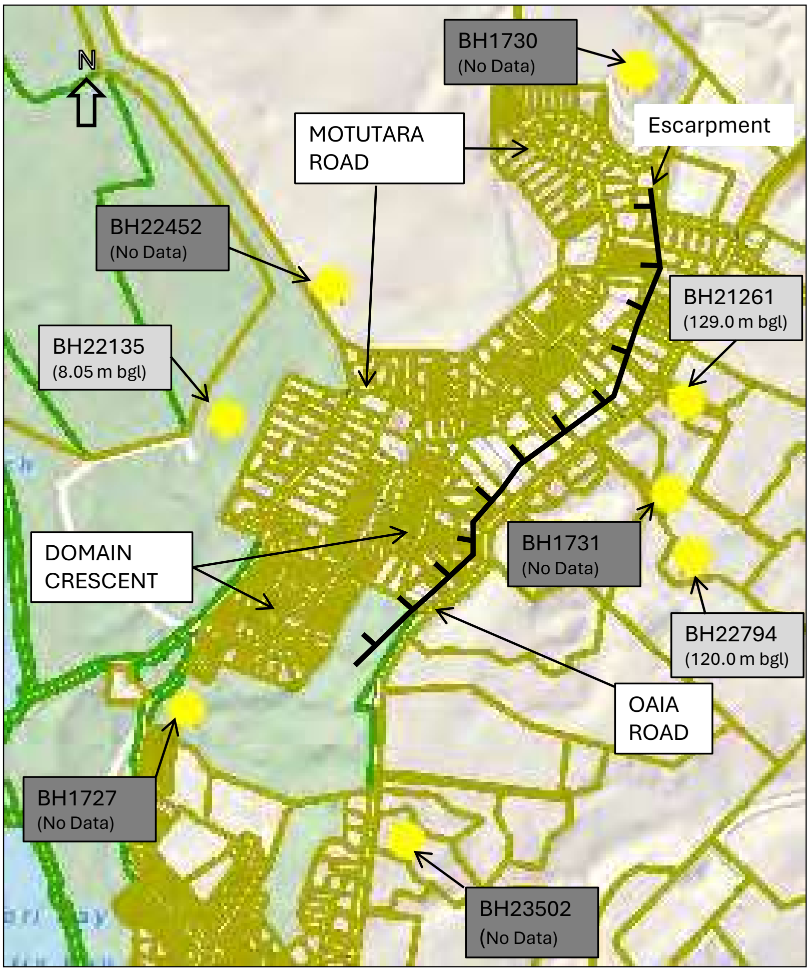


Figure B22 *Historical well location plan with water level, where known (measured between 2004 and 2007). Supplied by AC.*

B4.3.2 Groundwater interpretation

From the subsurface and surface groundwater data/observations, it is inferred that:

- A ‘regional’ groundwater table is located within Awhitu Formation sands, at or above the unconformity with underlying Waitakere Group Deposits, which are expected to represent a significant change (decrease) in relative permeability.
  - Historical data (Figure B22) suggests Waitakere Group may have been encountered east of the escarpment, at an RL approximately 30-40 m below its base elevation. The unconformity was not encountered below the study area other than at the southern end, in BH-M04.
  - It is unlikely that this regional groundwater table has any influence on the groundwater recorded in the study area.
  - All piezometers installed by GHD are located within overlying Awhitu Group deposits and record perched groundwater levels at significantly higher elevations.
- The Awhitu Formation sands contain a series of perched aquifers, some of which daylight as springs within the escarpment and that have variable (often none to minimal) connection to surface rainwater input.
  - They are bounded by discontinuous, relatively lower permeability layers/beds of silt/clay and limonite within the Awhitu Formation sands. The continuity of the aquifers is therefore a function of these layers/beds.

The relationship between the local groundwater level and pressure in the perched aquifers during peak or long duration rain events (such as Cyclone Gabrielle) is uncertain given there is no continuous subsurface data to date across an event of this magnitude. It is judged that the vertical and horizontal flow of groundwater within the Awhitu Formation sands is highly variable across spatial and temporal domains. Individual perched aquifers may be influenced by surface rainfall infiltration. It is also possible that, following the 2023 landslides, shallow perched aquifers have been destroyed or modified because of loss of overlying soils. This is partly supported by anecdotal observations of changes at springs from residents.

B4.4 Surface water

The escarpment is a significant barrier to the direction that surface water flows across the study area. Rainwater collects and flows due east above/behind the escarpment and due west within or below the escarpment.

Within the escarpment, flow paths are further controlled and concentrated by the smaller catchments defined by confining ridgelines and spurs, generally at right angles to the slope. These are summarised in Figure B3 for the study area.

The built environment of the local area, both above and below the escarpment, has resulted in the addition of impermeable land cover (hardstands/driveways, houses) and diversion of three waters (stormwater and septic water lines from residential property and stormwater drainage within public and private roads). The potential for any of these built structures to influence the natural surface water flow paths was assessed by reviewing AC supplied information for thirty-five properties located on Oaia and Motutara Road, as well as the stormwater catchment system within Oaia Road (GHD 2023 ‘Desktop Assessment Report’; GHD 2023 ‘Oaia Road and Edwin Mitchelson track Investigation Report’). It was concluded that:

- None of the private property stormwater / wastewater discharge was directed toward the observed landslides or damaged by them, except for 225 Oaia Road
- The existing stormwater catchment system on Oaia Road is adequately sized and draining away from (east of) the escarpment crest
- The table drains along Edwin Mitchelson track have been blocked by landslide debris.

Thus, GHD do not consider there to be any evidence for instigation or worsening of any observed 2023 landslides from built structures, from the available data reviewed.

B4.5 Ground model of study area

B4.5.1 Distribution of geological units

The surface morphology of the study area is the result of it being uplifted and tilted to the north-east unconformity of the underlying Waitakere Group deposits (Section B3.2.2). Nihotupu and Waiatarua Formations outcrop directly south of the study area (see Figure A114), but dip below the surface to the northeast and were not encountered at surface or at depth (beyond the location of BH-M04). Awhitu Sand Formation has been deposited and uplifted on top of this contact, thus sharing similar structural orientation, evident from silt/clay beds in outcrop (see Figure B23).

Previous studies (Hayward, 2022; Wright 1966) have suggested Waitakere Group deposits were located directly at the base of the escarpment however GHD’s 2023 ground investigations and mapping do not provide evidence for this. The unconformity is illustrated on cross-section A-A’ (see Figure A120).

B4.5.2 Material properties, Awhitu Sand

The in-situ strength profile of the Awhitu Sand formation increases with depth, observed from increasing SPT ‘N’ values within boreholes. This is interpreted to be the result of increasing quantities of iron cement within the sand and leaching associated with the development of an in-situ weathering profile from the surface. Engineering geological cross-sections (see Figures A120-124) illustrate this with the inferred boundary between less cemented and more cemented sands/sandstones. Significant uncertainty in spatial constraint of this zone is expected, given the lack of subsurface data points available.

Recently exposed sands (landslide slip surfaces) often retain near-vertical bluffs and rock mass fabric (block jointing and bedding, Figure B15); however, it is easily disrupted when physically agitated or when water is passed through it, as observed by sections of shallow core having disaggregated upon recovery. This is not observed with core at depth.

Silt/clay rich beds and thinner lenses are encountered randomly at depth with poorly defined lateral connection. They are not interpreted to be continuous over the study area however are observed to extend at least 100 m laterally approximately (Figure B23). These layers are often associated with areas of flatter slope profile, illustrated as ‘mid-slope benches’ on Figures A112-116. Organic layers are less common and only observed as <1.0m layers/lenses within borehole core (Figure B17).

B4.5.3 Groundwater

There is likely a deep regional water table (probably draining to sea level) well below the escarpment. The silt/clay beds within the Awhitu Sand influence groundwater movement and result in localised perched aquifers some of which are directly affected by rainfall (Section B4.3).

B4.5.4 Surficial deposits

Ancient deposits of colluvium (and potentially intermixed alluvium) are present at the base of the escarpment along sections of Domain Crescent and Motutara Road (Figure B11 and Figure B12; Table B6). An interpretation of their spatial extent, based on where the material was recovered within boreholes, is given in Figures A114,115,112 and 123. It is acknowledged that there is uncertainty with the extent of this material given the limited data points.

A graphical interpretation has not been given surrounding BH-M06 (Figure A122) due to the unknown lateral extent of the deep pocket of material encountered there (to at least 38 mbgl). Two interpretations are considered plausible:

- It represents a localised paleo-gully’ formed from a different sea level than present and has since been infilled by colluvial, alluvial and possible marine sources over time.
- It is a remnant of debris from a much larger ancient landslide that may encompass the northern area of Domain Crescent and explain the local higher elevation and irregular topography, possibly extending south of BH-M05.

The uncertainties associated with the nature and distribution of this material are not directly relevant to the scope of this assessment as it is not involved in any landslides associated with Cyclone Gabrielle. For this reason, it has not been considered further.

Figure B23 ***Example of lateral extent of near horizontal silt/clay beds within Awhitu Group, indicated by dashed line. Domain Crescent, M-LS20B for reference. Gentle dip due north – northeast.***

B4.6 Conceptual landslide model

B4.6.1 Mechanism and controls

The mechanism proposed for the shallow translational landslides that transition to high velocity debris flows is illustrated in Figures A127 and A128 and summarised as:

- Intense and prolonged rainfall delivers significant volumes of surface water into the valleys of the catchments along the escarpment slope. The water is sourced from overflow along the crest as well as directly intercepted by the catchment. An unknown (but possibly not insignificant) amount of groundwater saturates discrete areas of the slope from surface springs emitting from local perched aquifers within the Awhitu Formation.
- A relatively thin surficial layer of less cemented sands and historical colluvium rapidly becomes saturated through infiltration by surface runoff and groundwater. The surficial sandy soil layer weakens from rapid loss of cement.
- At a certain point (within minutes or hours depending on rainfall and runoff intensity) the weight and pore pressure within the already weakened layer cannot be sustained and a planar shear surface develops at the base of this zone (typically less than 1.5 m deep). This process may be accelerated by the innate erosive/dispersive nature of the Awhitu Formation. The slip surface often undermines shallow rooted vegetation and larger pine trees that were previously providing a degree of structural support to the surface soil but now become entrained.
- The high-water content of the surficial materials causes them to lose internal strength and flow downslope rapidly as a debris flow.

- Finer grained silt and clay layers within the Awhitu Formation that have a higher degree of cohesion may experience preferentially less infiltration and be less impacted by cementation loss, and in turn resist shear surfaces developing. This may cause the surface to ‘break out’ over the top and flow over otherwise in-situ soil and vegetation that then becomes entrained and transported downslope.
- Additions of relatively intact, less cemented sandstone blocks from isolated rockfalls on the upper escarpment are also released, inferred to be the result of pore pressure developing between near-surface joints and bedding layers, and carried downslope within the debris flow.

The mechanism proposed is supported by observational data across the study area, from the 1965 and recent 2023 events. Deeper seated landslides that may develop along circular slip surfaces (for example) have not been observed during either the 1965 or 2023 events within the escarpment study area and Awhitu Formation Sands geology. Deep seated rotational landslides from water driven events are therefore not considered possible at this site. This does not necessarily preclude the possibility of deep-seated earthquake-induced landslides on a larger scale than those caused by Cyclone Gabrielle, however the observation and assessment of these are outside of the scope of this assessment.

B4.6.2 Uncertainties of landslide mechanism

Identified uncertainty or unknown processes and factors associated with the proposed mechanism of landslide development are:

- **Relative influence of surface vs groundwater in slip development:** Others (Wright, 1966; Hayward, 2022) have stated that groundwater fluctuations and spring emittance played a significant role within the 1965 landslides and by deduction this inference could be extended to the 2023 events. The especially wet summer season of 2023-2024 may have contributed to overall wetter soils and a relatively higher groundwater table. We do not disagree with this. However, without a continuous monitoring record of groundwater levels and rainfall prior to and during the landslide events, it is not possible to determine their relative proportional impact. Anecdotal commentary associated with springs along the face is difficult to rely on given the time of the event (night) and already significant volumes of surface/sheet flow that would affect the reliability of observations. We suggest that surface water (rainfall and runoff) during the event had the predominant impact based on the groundwater data collected to date which indicates only minor fluctuations following subsequent rain events.
- **Landslide reactivation and retreat ‘lifecycle’ across escarpment:** Recently failed areas now expose fresher more intact material within the slip face and are therefore less likely to generate future large landslides compared with neighbouring catchments which did not recently experience them and thus have a greater layer of weaker surficial material. It is possible that other factors would still have greater influence of the location and frequency of landslide occurrence, for example: size of confining catchment, slope angle, density of springs. The recurrence of significant landslide activity in 2023 at the same location as the two large landslides of 1965 must also be considered. Without sufficient record of multiple large events like this, preferential retreat/erosion cycles in one section of escarpment vs another is plausible, but unknown.
- **Removal of native fauna and/or replacement with exotics:** Accompanying the development of the Muriwai community native vegetation has been removed and replaced by exotic species (mainly pine trees). The latter are particularly prominent along the crest of the escarpment as wildling pines, which were commonly observed to be entrained within slip debris and in some cases increased the hazard of the landslides given their destructive force on built structures. It is not clear whether the addition of pine trees on the slope increased the probability of landslide development, but it is considered possible given they are significantly heavier than most surrounding native vegetation and are prone to windfall due to their shallow root systems.

B5. Characterisation of landslide hazard

B5.1 Morphology

Refer to Appendix B-4 which catalogues the main features of all landslides mapped in 2023. Dimensional values of the landslides are given in Table B8. Estimated volumes and (run-out) lengths are also reproduced in Table B9.

We have used the following terminology, which is in broad accordance with that of Hungr et al (2014).

B5.1.1 Definition of landslide type(s)

The landslides mapped on the Muriwai escarpment are *shallow translational slide movements* within Less Cemented Awhitu Formation sands. Once mobilised, they develop into *high-speed debris flows* down steep slopes (approximately more than 45° typical) until arresting at or near the base where they either encounter flatter topography or an existing dwelling, or both.

- There are often instances of rockfall that releases from near-vertical bluffs formed by some of the larger landslides main scarp (headscarp), resulting from apparent near-surface rock mass jointing within the Awhitu Formation material that creates blocks of less than 1m3 volume.

B5.1.2 Shape and size characteristics

- Usually have a relatively large run-out length compared with the width at the main scarp, consistent with typical debris flows. Less common, smaller landslides of less than 50 m^3 recorded with runouts of similar values to their widths. Figure B24 and Figure B25 show typical examples of the shape and size of single landslides, and merged larger landslide areas, respectively.
- The landslides expose less cemented Awhitu Formation sands with silt and clay beds, along the sliding surface (Figure B23). The height of observed main scarps and corresponding depth of slip surface relative to the pre-existing ground profile was observed during field mapping to be between 0.5 m and 1.5 m.
- Tension cracks above the crest of the escarpment and headscarps of the larger landslides were not generally observed in field mapping. Some evidence of these was observed in several properties along Oaia Road, however it is unclear if these were present before the event. In these instances, the observed cracking is close to the escarpment crest and thus may represent local relaxation and toppling of the material at the crest.
- Figure A126 shows that within the larger slides the average depth of the depletion zone (above the slip surface) is quite variable. Similarly, the zone of accumulation varies in thickness. Note the limitations with the data to develop Figure A126 is described in Appendix B-5.

Table B8 Summarised dimensional values (size and shape) of 2023 landslides

Summarised values for 2023 landslides	Main headscarp width (m)	Debris runout (m)
Average	**22**	**48**
Maximum	96	137
Minimum	4	8
Standard deviation (1)	19	36

B5.1.3 Distribution

- Most landslides originate (and form their main headscarp) near the crest of the escarpment and travel slightly beyond its base, with the largest slides traversing the full length (distance) to Motutara Road. Smaller slips originate within the escarpment or the main spurs from it.

- There are four distinct areas along the escarpment where landslide activity was more concentrated and debris fields merged. These are illustrated in Figure A126.

B5.1.4 Debris

- The debris is a mixture of residual soil and Less Cemented Awhitu Formation sand, silt, and clay, with ‘blocks’ of less cemented sandstone, entrained surficial vegetation and debris from impacted dwellings.
- The volume of debris accumulated at the base of the slopes tends to be a function of the confining catchment, with some debris fields being the merging of many separate depletion zones and in some cases originating from areas with merged head scarps (see Figure B25). The risk associated with this merging is addressed in Appendix D.
- The fluid nature of the debris flow means its travel path is strongly governed by the encompassing catchment / topography. This creates inconsistency in the spread of damage to the built environment at the base of the escarpment slopes.
- Field-based observations of inflicted damage suggest that debris travel velocities were ‘very rapid to extremely rapid’ (3 m/min to greater than 5 m/s; in accordance with Cruden & Varnes, 1996, ‘Figure 3-17’ and ‘Table 3-5’). Anecdotal evidence broadly agrees with these estimates.
- Silt and fines carried in solution during initial failure and deposition were re-mobilised periodically following later rain events.
- The cemented blocks from the isolated rockfalls typically disintegrated into the larger debris flow but occasionally reached the toe of the extent of the run out without being destroyed (e.g. landslides M-LS03, M-LS04, M-LS04a, see Figure A114)
- There is general uncertainty and expected error in the exact definition of the point of inflection between the depletion compared with the accumulation zones within each landslide given the colluvial debris are often observed to begin depositing part way up the landslide face in a thin veneer. This is difficult to map accurately.

Figure B24 ***Typical features of single landslides areas.***

Figure B25 ***Typical features of larger, merged landslide areas.***

B5.1.5 Frequency of occurrence

The rainfall data presented by AC (Table B3 *'Measured and estimated rainfall'*) indicates a peak rainfall total for Muriwai during the Cyclone Gabrielle event of 146.9 mm, occurring over 12-hour period. This total is >100-year event at a 12-hour duration. The data suggests that for the 12-hour duration rainfall the Annual Recurrence Interval (ARI) is >100 years and may be in the order of 250 years. However, we understand that the calculation above the 100-year assessment becomes increasingly unreliable, primarily because of the relatively short statistical rainfall records available in New Zealand. For the other durations modelled, the rainfall was below the 100-year event.

For the risk assessment discussed in the Appendix E report we have assumed that the annual likelihood of a landslide event that is similar in magnitude to the February 2023 event is about 1 in 100 (i.e., 0.01). The assumption of 1 in 100 based on rainfall frequency is a simplifying and possibly conservative assumption that we consider reasonable. It does not consider other factors that could potentially affect stability (antecedent conditions, geology, groundwater conditions, slope height and angle, vegetation, surface water management- overland flow path, overflow from water storage tanks, effect of effluent disposal field) all of which vary between locations and are difficult to quantify.

Based on discussions with AC, we understand that no reliable storm ARI value is available for the 1965 landslide event due to the lack of data. Hayward (2022) states that the 1965 landslides followed 2 days of unusually heavy rain, with a nearby gauge recording 95 mm on August 25 to 26, plus 45 mm in the 12 hours preceding the landslides that occurred on 27 August 1965. However, the author goes on to mention that this is somewhat less than that recorded officially for the 3-day period at Whenuapai (220 mm) and Manukau Heads (190 mm). Review of publicly available NIWA rainfall data suggests the ARI for a day-day rainfall event of similar magnitude is less than 100mm. The 1965 landslide event affected a considerably smaller area of the Muriwai escarpment than the recent 2023 event, suggesting that the triggering rainfall event was smaller. Considering the uncertainties above, we have assumed that a rainfall event with an ARI of about 50 (assuming current climate conditions) could trigger a similar landslide event to that experienced in 1965.

As discussed above, the review of historical aerial photographs and available literature did not reveal evidence for any other landslide events besides the 1965 event. It is considered likely that small landslides (perhaps less than about 20 m^3) could occur more frequently than an event similar in magnitude to the 1965 event. These events could easily go unnoticed (or become forgotten) should they occur in vegetated areas or not result in damage to dwellings.

When more data is available it is common practice to develop landslide size frequency models to present judgments and help predict the future size and frequency of landsliding (e.g. Moon et.al 2005, Hunter et al. 2022). Given that only two landslide-initiating events are known at the site, as well as the uncertainties with rainfall data, we do not believe this approach is practical for this site based on the available data at this time.

B5.2 Empirical landslide runout assessment

B5.2.1 Background

Empirical methods have been used to further compare the landslide runout distances predicted using RAMMS (see Appendix D report) and the observed landslide runouts.

The “fahrböschung” angle (F-angle) assessment is a commonly used, long established rapid screening method for estimating landslide runout. Heim (1932) defined the “fahrböschung” angle as the tangent of the ratio of fall height (H) to horizontal runout distance (L) between the crest of the source zone and toe of the deposit as presented in Figure B26).

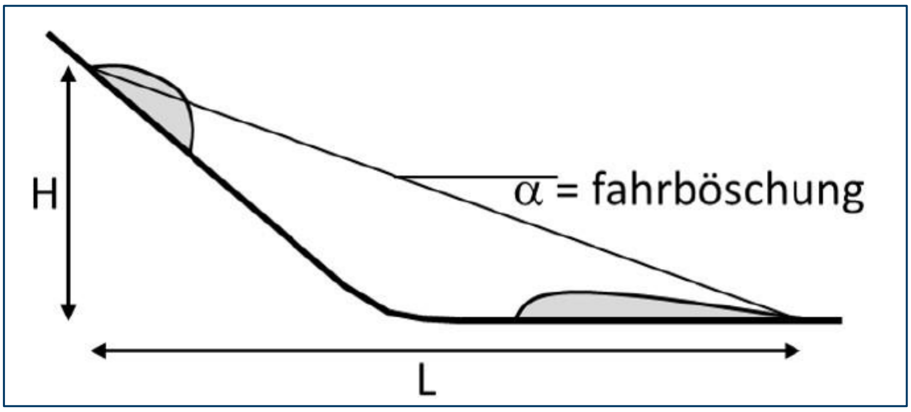


Figure B26 Fahrböschung angle definition after Heim (1932).

Other authors refer to the F-angle by different terms although the definition is the same. For example, Hunter and Fell (2002) adopt the term ‘travel distance angle’ (referred to by other workers as ‘reach angle’ or ‘angle of reach’). There are many published empirical methods for estimating landslide travel distance (or travel distance angle). Many of these methods are based on slide volume as the main dependent variable (Heim 1932; Scheidegger 1973; Hsu 1975; Smith and Hungr 1992; Corominas 1996; Finlay et al 1999; amongst others). Other authors have proposed empirical expressions based on the inverse relationship between the tangent of the reach angle (H/L) and the landslide volume (i.e. Finlay et al 1999).

Hungr et al. (2005) reported that the volume dependence of the reach has been questioned by several authors for both large landslides (Hsü 1975, Smith and Hungr 1992) and small landslides (Hunter & Fell 2003) and other alternative explanations have been proposed. These works show that there is a lack of agreement among researchers, and opposite conclusions have been derived from these simple relations. Consequently, Hungr et al. (2005) recommends that the use of the F- angle to determine travel distance is made with care.

Finlay et al.’s (1999) data was a mixture of good and modest quality information which is reflected in the large scatter of the predicted travel distances. Hungr et al. (2005) states that Hunter & Fell (2002, 2003) revised this work using more selective good quality data and their recommendations are to be preferred. Hunter & Fell (2002) found that the downslope angle below the source area, provides a useful method for prediction of the travel distance angle for “rapid” slides in natural slopes (Figure B27).

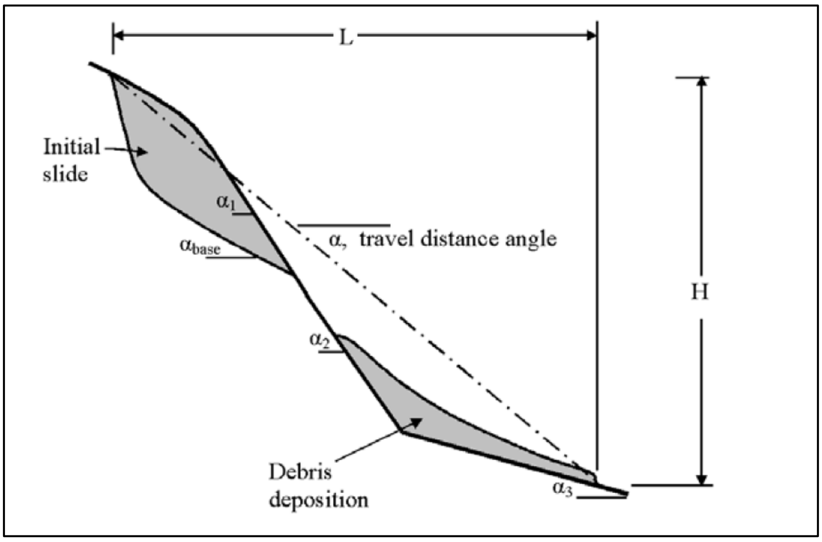


Figure B27 Definition of downslope angle below source area α_2 for slides on steep natural slopes (Hunter & Fell (2002))

B5.2.2 F-angle assessment

Following the February 2023 landslide event AC carried out an area-wide ‘F-angle’ assessment (documented in an internal Auckland Council memo dated 9/03/2023, document ID: AKLCGEO-1790012875-1831). The purpose of this assessment was to inform decision making about managed temporary access (to enable residents to retrieve property, or insurance assessors to assess losses) and amend placard designations. The assessment was not intended for use in long-term decision making or planning.

The AC study used approximately 15 cross sections through landslides to calculate F-angles. The results ranged from 22° to 25°. This range of angles was projected downwards from the crest of the cliff scarps to predict the possible travel distance of future landslides.

As part of this study, GHD carried out an independent F-angle assessment, using new mapping and the LiDAR data captured on 18 February 2023, of 32 landslides located across the escarpment. A summary of the assessment is presented in Table B9. Volumes were estimated from the mapped area of the depletion zone of each landslide, multiplied by the approximated averaged depth; the latter value is given for each landslide in Appendix B-4.

Some of the calculated F-angles should be considered with caution because landslide flows at some locations were affected by built structures such as driveways and houses. Furthermore, in some instances a number of different landslides coalesced and it was not possible to determine where individual landslides stopped.

The assessment revealed a wide range in F-angles ranging from about 16° to 42°. The range is likely attributable to the effects of local topography, degree of channelisation and potentially obstacles such as vegetation and built structures. This review of F-angles at Muriwai suggests that while it is a useful rapid screening method for landslide runout prediction, the range in the data makes it difficult for this method to be used in isolation.

We have also compared the relationship between landslide volume and runout distance by presenting the data on a H / L vs volume plot (Figure B28). As is apparent from the plot, there is a broad scatter of data with a poor correlation between the H / L ratio and landslide volume. Runout estimation methods based on a volume relationship such as Finlay et al (1999) therefore do not appear to be useful in the case of Muriwai. This is consistent with commentary in the literature by Hungr et al. (2005).

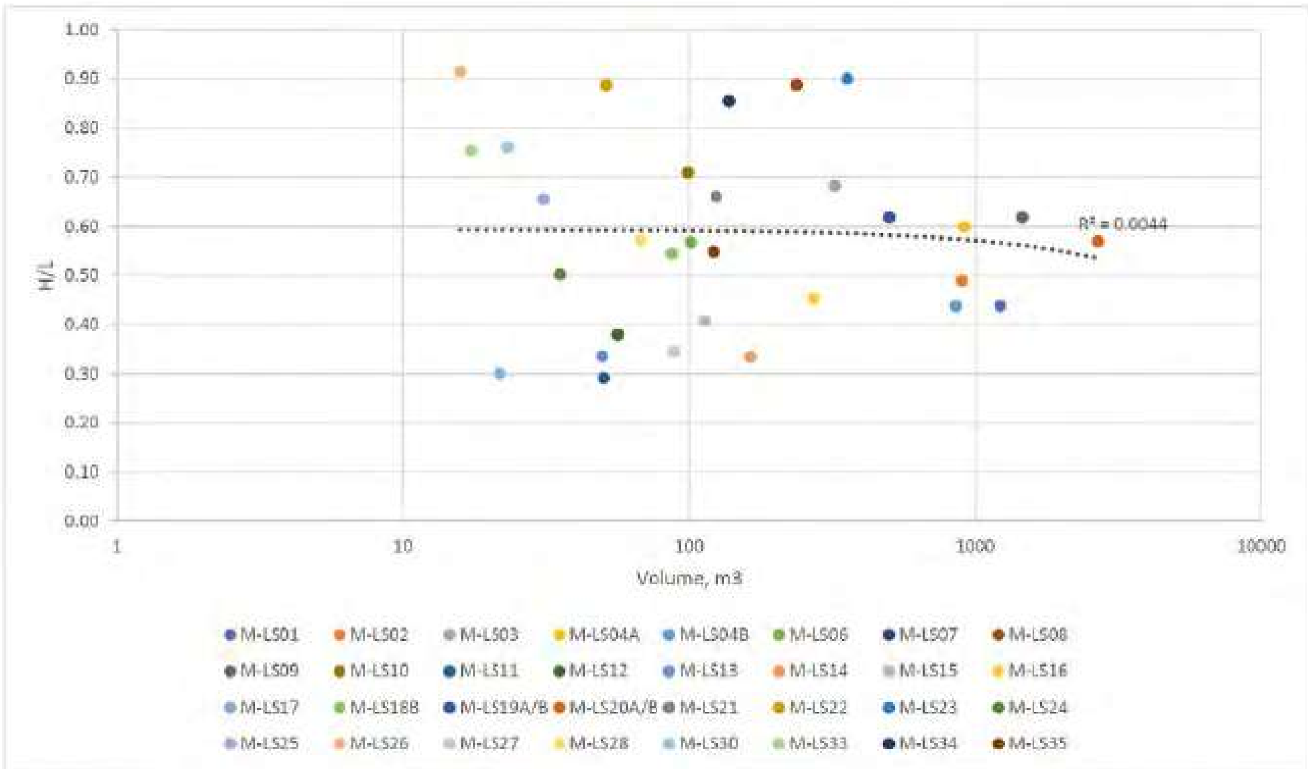


Figure B28 Height / Length ratio vs volume plot for all Muriwai landslides on the main escarpment

B5.2.3 Hunter and Fell (2002) empirical method

Using the Hunter & Fell (2002) method for “rapid” landslides the travel distance angle of the failed slide mass is calculated from assessment of the failure mechanics of the initial slide (whether contractile or dilative on shearing), the type of slope, slide volume, geometry of the slope at and below the slide source area, and the degree of confinement of the travel path of the landslide. Given the predominantly sandy composition of the Muriwai debris flows it is assessed that the material will dilate following the initial failure.

The Muriwai landslide data is presented on a H / L ratio vs tangent of the downslope angle plot according to the Hunter & Fell (2002) method (Figure B29). This also includes data for the 1965 landslide. Regression lines have also been established based on the degree of confinement. The regression line for a ‘partially confined’ travel path was found to be very similar to the Hunter & Fell (2002) regression line for a ‘partially confined’ travel path.

Table B10 presents the predicted travel distance angles for a range of slope angles using this method.

Comparison of the method with the known F-angles calculated for several of the February 2023 Muriwai landslides typically found agreement within a few degrees.

The predicted travel distances using the Muriwai relationship are very similar to the Hunter & Fell (2002) method, albeit usually at the higher end of the travel distance angle range. Based on the results of this exercise there is a good correlation between landslide runout and the downslope angle for the landsliding at Muriwai, meaning that landslide runout will vary across the escarpment depending on the local geomorphology. The close similarity between the Hunter & Fell (2002) predictive method and the Muriwai relationship probably suggests that while some variability is to be expected, future landslides are unlikely to travel appreciably further than the observed February 2023 runout distances.

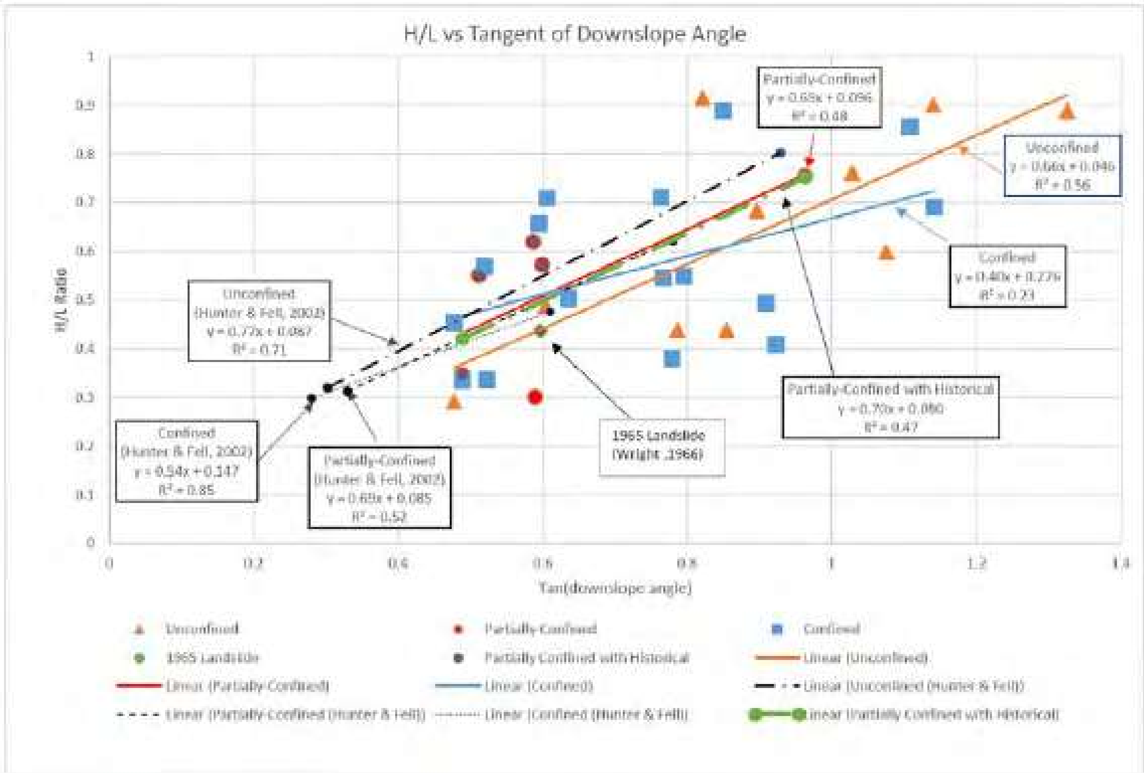


Figure B29 *H/L versus tangent of the downslope angle α_2 plot for Muriwai data together with Hunter & Fell (2002) relationships for rapid slides on steep natural slopes in dilative soils.*

Table B9 Summary of F-angle assessment

Landslide ID	Length (m)	Height (m)	Downslope Angle (α_2)	F-Angle	Estimated Landslide volume (m^3)	Comments
M-LS01	142.8	62.6	38	24	1222	
M-LS02	133.6	65.396	31	26	899	
M-LS03	89.1	60.9	42	34	324	
M-LS04A	108	64.7	47	31	914	
M-LS04B	147.8	64.7	41	24	855	Length measured from landslide centreline due to channelised landslide flow
M-LS06	113.4	64.4	27	30	101	
M-LS07	59.5	42.2	31	35	99	Difficult to determine toe of slide due to coalescence of adjacent debris flows
M-LS08	69.2	61.5	40	42	237	Difficult to determine toe of slide due to coalescence of adjacent debris flows
M-LS09	131.4	81.4	30	32	1457	
M-LS10	88.7	63	37	35	99	
M-LS11	44.2	12.9	25	16	50	Slide originated on lower escarpment slope. Length measured from landslide centreline due to channelised landslide flow
M-LS12	84.3	32.02	38	21	56	
M-LS13	57.7	19.4	28	19	50	Flow appears to have been channelised along driveway - runout may be misleading
M-LS14	66.4	22.2	26	18	164	Length measured from landslide centreline due to channelised landslide flow
M-LS15	48.1	19.6	43	22	113	
M-LS16	44.3	20.1	26	24	272	
M-LS17	23.6	7.1	31	17	22	Small, localised landslide on lower escarpment slope
M-LS18B	131.7	71.7	37	29	87	Length measured from landslide centreline due to channelised landslide flow
M-LS19B	116	63.8	27	29	500	
M-LS20B	139.1	68.6	42	26	2692	
M-LS21	57.3	39.6	49	35	124	

Landslide ID	Length (m)	Height (m)	Downslope Angle (α_2)	F-Angle	Estimated Landslide volume (m^3)	Comments
M-LS22	17.9	15.9	53	42	51	
M-LS23	30.3	27.3	49	42	357	
M-LS24	39.2	19.7	32	27	35	
M-LS25	41.6	27.3	31	33	31	
M-LS26	9.4	8.6	39	42	16	Small, localised landslide on lower escarpment slope
M-LS27	35.8	12.4	26	19	89	Small, localised landslide originating on ridgeline - lower escarpment slope
M-LS28	20.8	11.9	31	30	68	
M-LS30	13.4	10.2	46	37	23	
M-LS33	26.9	20.3	44	37	17	Small, localised landslide on lower escarpment slope
M-LS34	63.7	54.5	48	41	138	Difficult to determine toe of slide due to coalescence of adjacent debris flows
M-LS35	81.8	44.9	39	29	122	

Table B10 ***Summary of predicted travel distance angles***

Downslope Angle (°)	Predicted Travel Distance Angle (°) (Hunter and Fell (2002) empirical method)*	Predicted Travel Distance Angle (°) – Muriwai Regression Data
20	19	19
25	22	23
30	25 - 26	26
35	28 - 30	30
40	31 - 34	34
45	34 - 38	38
50	38 - 42	43
55	43 - 47	47
60	47 - 52	52

*Confined and partly confined travel pat

B6. Landslide hazard assessment

B6.1 Inferred future landslide source areas

The distribution of potential landslides is an important consideration for the assessment of future debris flow risks (see Appendix D for rationale and reference to figures that show inferred potential landslide sources). Appendix E quantifies the relative risk of damaging landslides for each zone.

Potential landslide failure zones have been identified based on having similar geomorphology (ground shape) and geology to February 2023 landslide source areas. For example, the bowl-shaped head-scarp shape of recent landslides observed at the crest of the escarpment is similar to the shape of the escarpment where failures did not occur in 2023 (Figure B30) but have almost certainly occurred at some time in the past. Hence, we infer that the whole of the escarpment has similar landslide susceptibility due to the likely similar conditions of geology and possibly groundwater. We have assumed that future landslides on the escarpment have the potential to fail with similar damaging effects as the February 2023 landslides. Inferred landslides were used as RAMMS debris flow source areas to model potential future landslide hazard areas (see the Appendix D RAMMS analysis report).

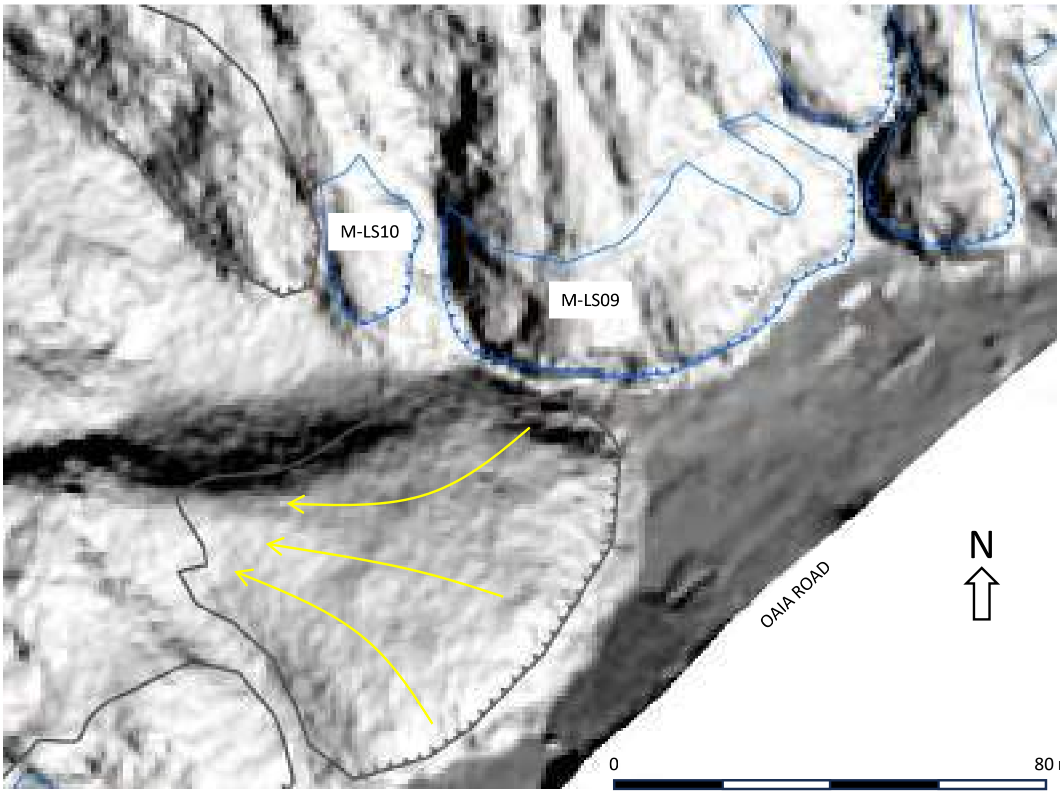


Figure B30 ***Potential landslide failure zones have been identified by GHD based on having similar geomorphology (ground shape) and geology to February 2023 landslide source areas. The above example shows a potential landslide source zone (grey outline) that has similar bowl-shaped characteristics to recently failed blue areas. Yellow lines indicate expected debris flow path. Background surface model has a 'hill shade' applied to highlight the geomorphology. Location is below the escarpment and west of Oaia Road.***

B6.2 Potential for deep-seated landslides within Awhitu Formation

Two instances of deep-seated landslide activity are observed or inferred within Awhitu Formation sand surrounding the study area. These features are located outside of and within the study area, respectively. The mode and cause of failure are not considered to be related to the trigger event associated with the 2023 landslides resulting from Cyclone Gabrielle.

- A deep-seated translational landslide is present within the Awhitu Formation, south of the study area, immediately south of Waitea Road (Figure B31). Its geomorphology is suggestive of an earth flow. The toe region of the landslide appears to be un-buttressed and eroding into the ocean over a large cliff line. The outcropping Nihotupu Formation at the toe of the slope is inferred to control the depth of slip by acting as a relatively impermeable barrier to groundwater flow. This underlying unconformity is the same feature interpreted to dip below the study site from the southern end of Domain Crescent (Section B4.5).
- The possibility for a large, 'ancient' landslide identified from surface geomorphology and subsurface core recovered in BH-M06 was raised in Section B4.5 and. A feature of this scale would likely be complex in its mode and mechanism of failure and, as implied from BH-M06, the principal slip surface may extend several tens of meters below ground.

These modes of landslide failure are not considered applicable to the study area and the debris flow hazard off the escarpment at Muriwai township.

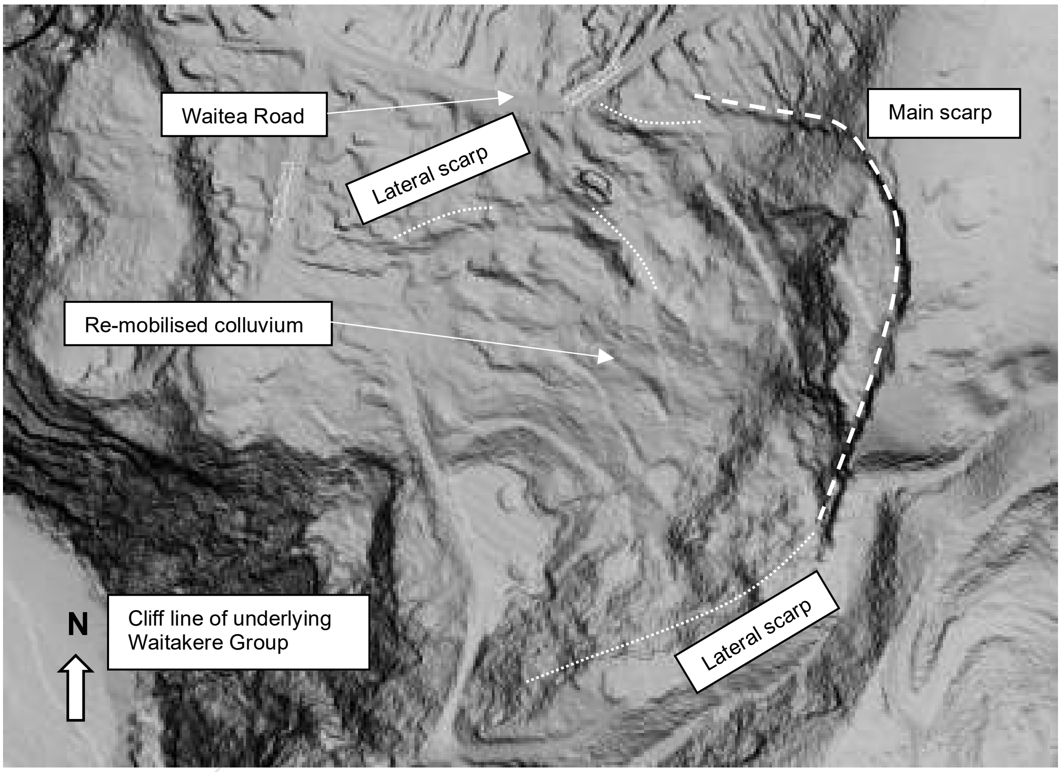


Figure B31 ***Deep seated landslide (earthflow) within Awhitu Sand Formation, underlying contact with Waitakere Formation daylighting in toe area (cliffs). Background surface model has a 'hill shade' applied to highlight the geomorphology.***

B6.3 Geomorphological landslide zones

B6.3.1 Definition and overview of zones

The study area has been divided into six geomorphological 'zones' based on the surface topography, February 2023 landslide characteristics and general geomorphology. The purpose of this is to differentiate areas according to their susceptibility to large-scale[3] landslides. The life risk to residents for each zone is considered separately in the risk assessment (see overall report Appendix E).

To help define the zones, we applied a colour scale to a plan of Muriwai (Figure A125 in Appendix A) to highlight the topographic variation and show areas that are steeper than others. Cross sections were then used to generate slope profiles, mostly normal to the Muriwai escarpment, but in some cases below the escarpment, and the profiles were overlain to identify similarities and differences.

[3] In this report 'large scale' landslide hazards refers to landslides originating from the main escarpment that typically have a volume of more than about 50 m^3 with the potential to cause total or partial collapse of a dwelling.

The slope angle and approximate height of the steeper section of the profile is shown for each zone in Table B11. This estimate is subjective and is an approximation only, however, it is a sound basis for differentiating between zones.

Table B11 Summary of slope angle and height for zone profiles (zones coloured to match profile colours)

<table>
<tr><th>Zone</th><th>Average Angle</th><th>Minimum Angle</th><th>Maximum Angle</th><th>Approximate vertical height to nearest 10 m</th></tr>
<tr><td>1</td><td>30</td><td>26</td><td>31</td><td>20</td></tr>
<tr><td>2</td><td>33</td><td>30</td><td>41</td><td>70</td></tr>
<tr><td>3</td><td>25</td><td>23</td><td>30</td><td>60</td></tr>
<tr><td>4</td><td>44</td><td rowspan="3">NOT APPLICABLE DUE TO VARIABLE SLOPE PROFILE SHAPES</td><td colspan="2">50</td></tr>
<tr><td>5</td><td>38</td><td colspan="2">30</td></tr>
<tr><td>6</td><td>39</td><td colspan="2">20</td></tr>
</table>

Figure B32 shows the slope profiles, coloured according to zone to allow comparison. The common point of reference for the profiles is the top of the slope (i.e. the top of the escarpment).

Similarly, comparison of the number of landslides and the distribution of these according to zone highlights the spatial variability of these (see Figure B33 and Figure B34).

The following sections describe the landslide and topographic characteristics of each zone referring to these data.

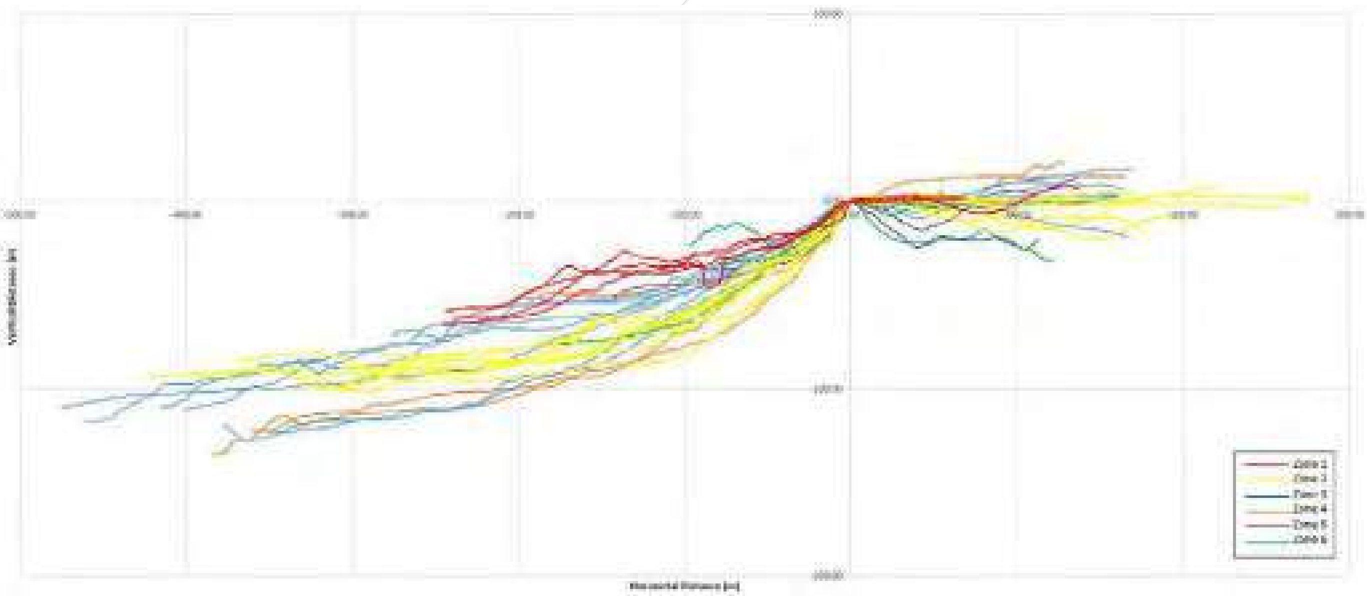


Figure B32 Slope profile comparison of 27 cross sections in Zones 1 to 6 (see Figure A137). Profiles are mostly viewed in a north-looking direction and have been centred on the crest of each slope (in most cases this is the top of the escarpment).

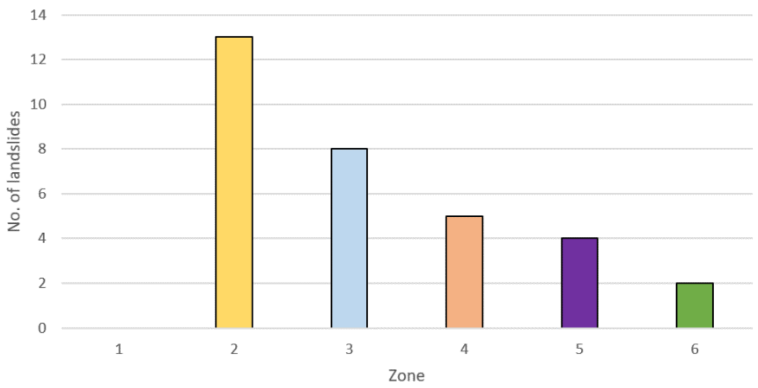


Figure B33 ***Number of February 2023 landslides per zone***

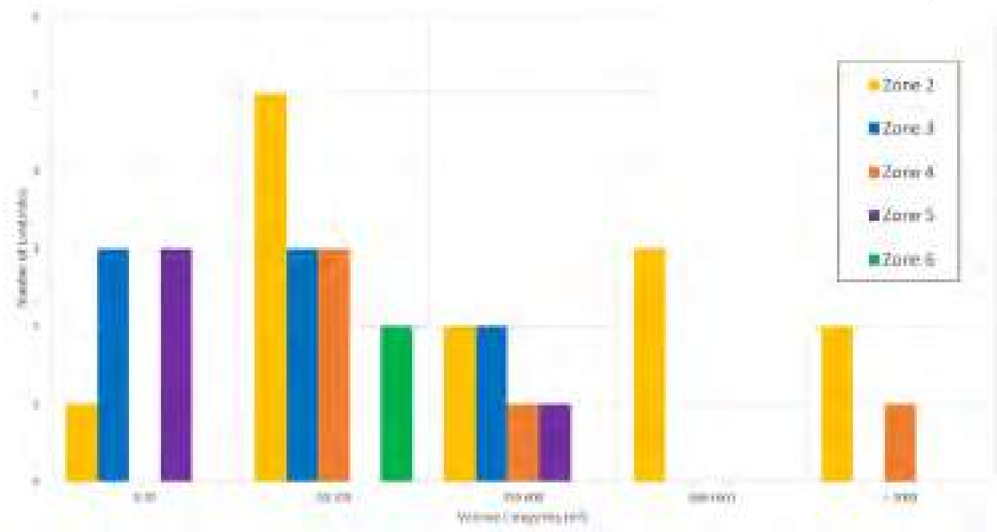


Figure B34 ***Number and size of February 2023 landslides shown per zone***

B6.3.2 Zone characterisation

6.3.2.1 Zone 1

Zone 1 is located at the northern end of Motutara Road north of, and including, 42 and 104 Motutara Road (see Figure B35). The features of Zone 1 are as follows:

- The steepest part of the slope at the top of Motutara Road is approximately 30°, which is relatively flat (see Figure B36).
- The vertical height of the slope at this steepness is approximately 20 m, which is one of the lowest on the escarpment.
- No large landslides occurred in this area in the February 2023 storm event.
- The general slope-facing direction is towards the southwest, which may not directly face the direction of origin for sub-tropical cyclone storm events.

When considering the potential for future landslides, we have considered that Zone 1 may have favourable conditions (low susceptibility) partly due to the location of Motutara Road at the upper part of the slope (i.e. in the vicinity of 42 Motutara Road), which may act to intercept and redirect surface flows from further up the slope, and partly due to its aspect. In addition, anecdotal evidence from community interaction is that the surface water conditions during the February 2023 storm were not notably extreme, with no observed concentrated flow.

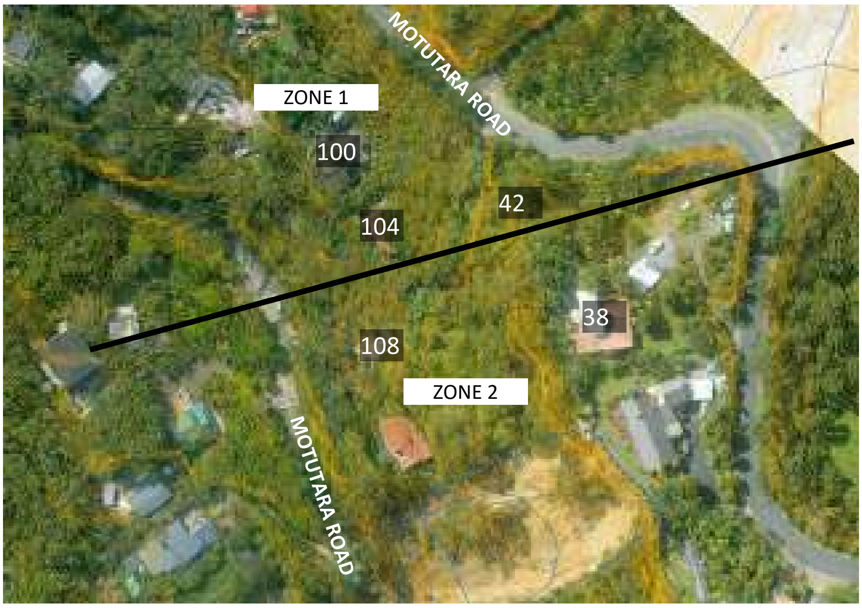


Figure B35 Location of the Zone 1 / Zone 2 boundary. North is to the top of the page.

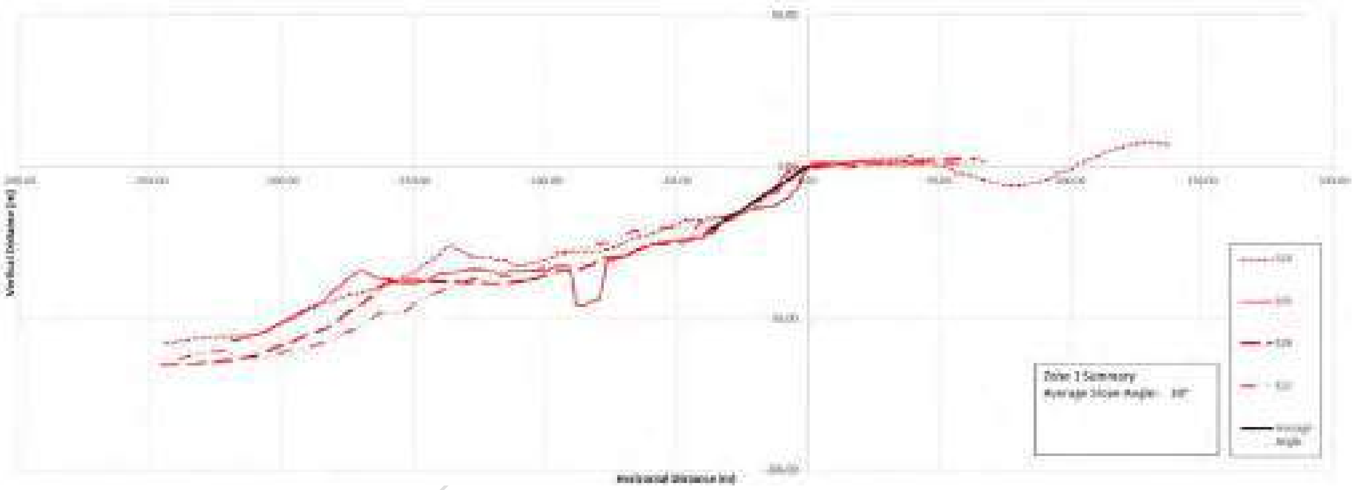


Figure B36 Slope profile comparison of Zone 1 surface cross sections (see Figure A137 for location of sections)

6.3.2.2 Zone 2

Zone 2 is the largest zone and is above Motutara Road. It is defined in the north by, and including, 38 and 108 Motutara Road (see Figure B35) while the southern limit of Zone 2 is bounded by, and includes, 228 and 230 Motutara Road (see Figure B43). The features of Zone 2 are as follows:

- The average slope angle is 33° but is locally much steeper (see Figure B37).
- The vertical height of the slope is greater than 70 m on average, which is the highest of all zones.
- Thirteen large landslides occurred in Zone 2 in the February 2023 storm, with two having a volume greater than 500 m^3. The landslides are commonly broader relative to other zones (e.g. Zone 3).
- The general slope-facing direction is to the west, which is expected to be towards future sub-tropical cyclone storm events.
- The shape of the escarpment tends to be mostly gently and continuously curving. Elsewhere on the escarpment, for example in Zone 3, there are many distinctive, tightly curved headscarp features.

The above observations align well with this area having the potential for multiple, highly damaging landslides, as was the case in the February 2023 event.

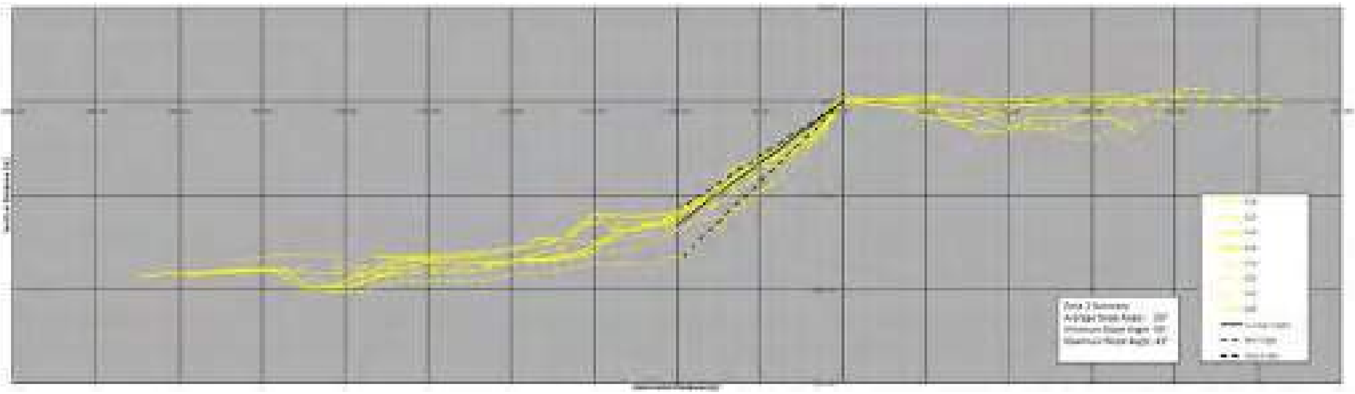


Figure B37 ***Slope profile comparison of Zone 2 surface cross sections (see Figure A137 for location of sections)***

6.3.2.3 Zone 3

Zone 3 is located at the Muriwai escarpment above Domain Crescent, being defined to the north by properties on the northern side of Domain Crescent (see Figure B43) and to the south by 63 Domain Crescent (see Figure B38). The features of Zone 3 are as follows:

- The slope is approximately 25° on average, which is relatively flat (see Figure B39).
- The vertical height of the slope at this steepness is approximately 60 m, which is relatively high.
- Eight large landslides occurred in February 2023, all with a volume of less than 600 m^3.
- The general slope-facing direction is to the west, which is potentially towards future sub-tropical cyclone storm events.
- The escarpment has many distinctive, tightly curved headscarps in marked contrast with Zone 2. Debris flows are typically more channelised in this zone.

The observations above indicate a regime with potential for large, destructive landslides.

Figure B38 ***Location of the Zone 3 / Zone 4 boundary. North is to the top of the page.***

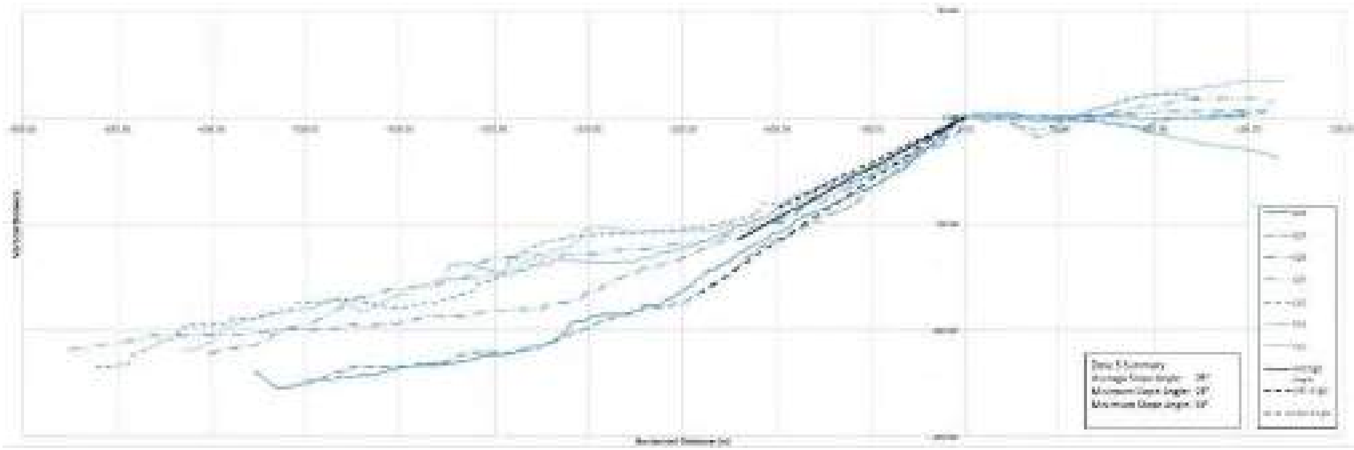


Figure B39 Slope profile comparison of Zone 3 surface cross sections (see Figure A137 for location of sections)

6.3.2.4 Zone 4

Zone 4 is located at the southern end of Domain Crescent between 47 and 61 Domain Crescent (see Figure B40 and Figure B38, respectively). The features of Zone 4 are as follows:

- The average slope angle is 44°, which is relatively steep (see Figure B41).
- The vertical height of the slope at this steepness is approximately 50 m, which is less than in Zones 2 and 3.
- Five large landslides occurred in February 2023, with one over 1000 m^3 in volume. Note that Zone 4 is smaller than other, similar zones and so the number of landslides may give a false impression of the exposure of dwellings at the slope base.
- This is the location of the large 1965 landslide (see Section B3.3.2).
- The general slope-facing direction is to the west, which is expected to be towards future sub-tropical cyclone storm events.
- The escarpment has many distinctive, tightly curved headscarps.

The observations above indicate a regime with a demonstrated potential for large, destructive landslides on a similar scale to Zone 2.

Figure B40 Location of the Zone 4 / Zone 5 boundary. North is to the top of the page.

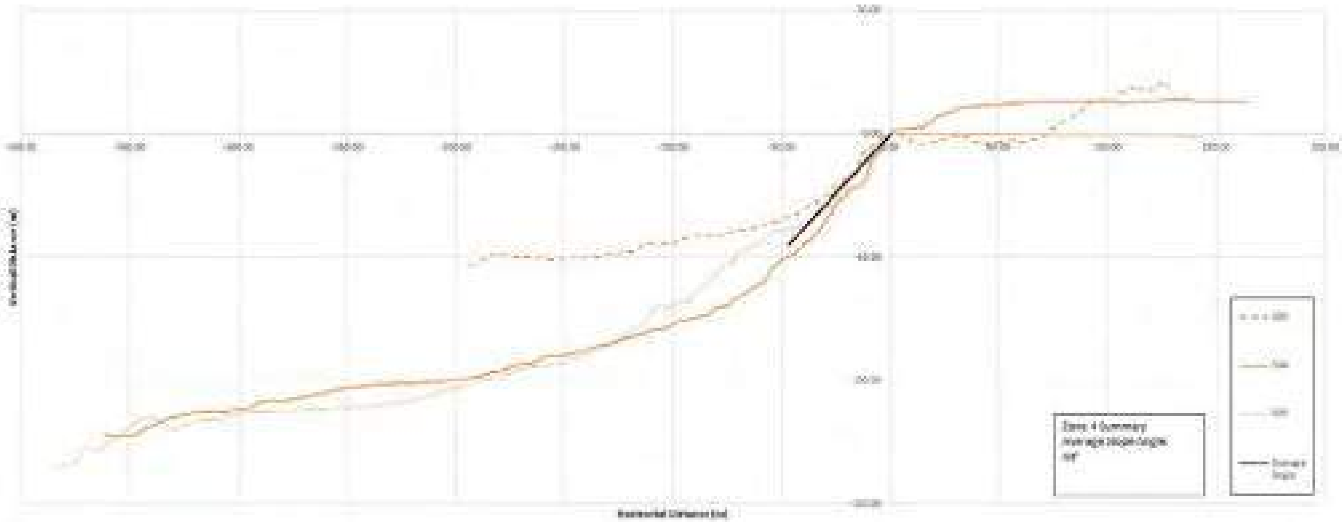


Figure B41 Slope profile comparison of Zone 4 surface cross sections (see Figure A137 for location of sections)

6.3.2.5 Zone 5

Zone 5 is the southernmost zone between Domain Crescent and Waitea Road. The boundary of Zone 5 is to the east of 39 and 41 Domain Crescent (see Figure B40). The features of Zone 5 are as follows:

- The slope is approximately 38°, which is derived from only two cross sections (see Figure B42).
- The slope facing Domain Crescent is one side of a ridge, meaning that the catchment for surface water or groundwater recharge is limited compared with escarpment zones. This may mean that Zone 5 is less susceptible to landslides.
- Four landslides occurred in the February 2023 storm, most of which were less than 50 m^3; none impacted dwellings.
- The general slope-facing direction is towards the northwest, which may be the direction of origin for future sub-tropical cyclone storm events.

When considering the potential for future landslides, we suggest that Zone 5 may have favourable conditions due to the topography, which does not encourage storage of groundwater behind the slope, and the limited potential for surface runoff to saturate the slope.

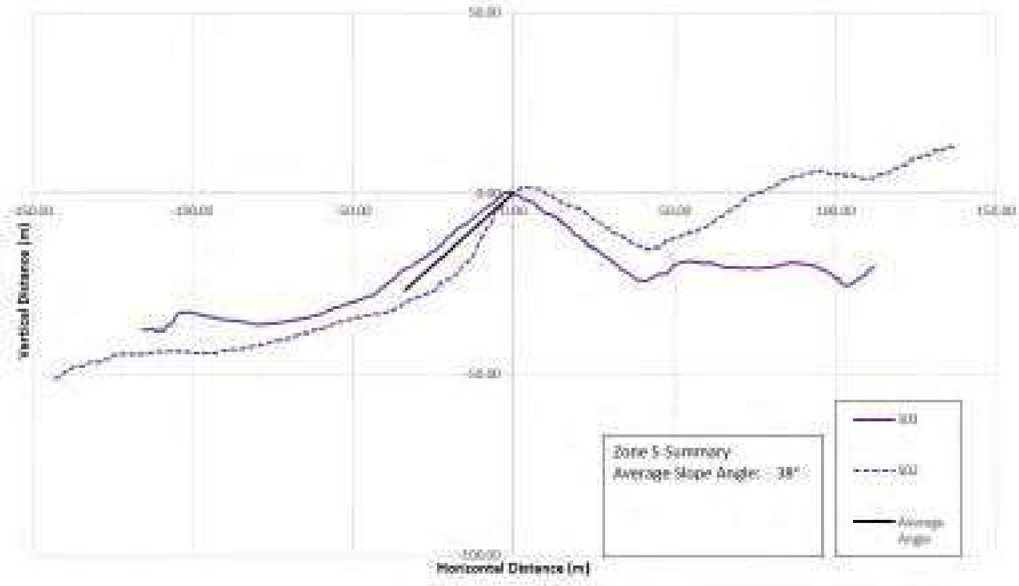


Figure B42 Slope profile comparison of Zone 5 surface cross sections (see Figure A137 for location of sections)

6.3.2.6 Zone 6

Zone 6 is located between Zone 3 and 2. It includes 264 Motutara Road to the west through to 232 Motutara Road to the east (see Figure B43). This zone is away from the Muriwai escarpment but is locally steeper than surrounding land. The features of Zone 6 are as follows:

- The average steepness of the three cut profiles is about 39°, although the variability of the profiles is noted (see Figure B44).
- The vertical height is approximately 20 m, which is relatively low.
- Two landslides in the range of 50 to 150 m^3 were recorded following the February 2023 storm event.
- The general slope-facing direction is towards the north.

When considering the potential for future landslides, we consider that Zone 6 may have favourable conditions due to the topography, which does not encourage storage of groundwater behind the slope, the low slope height, and limited potential for surface runoff/saturation.

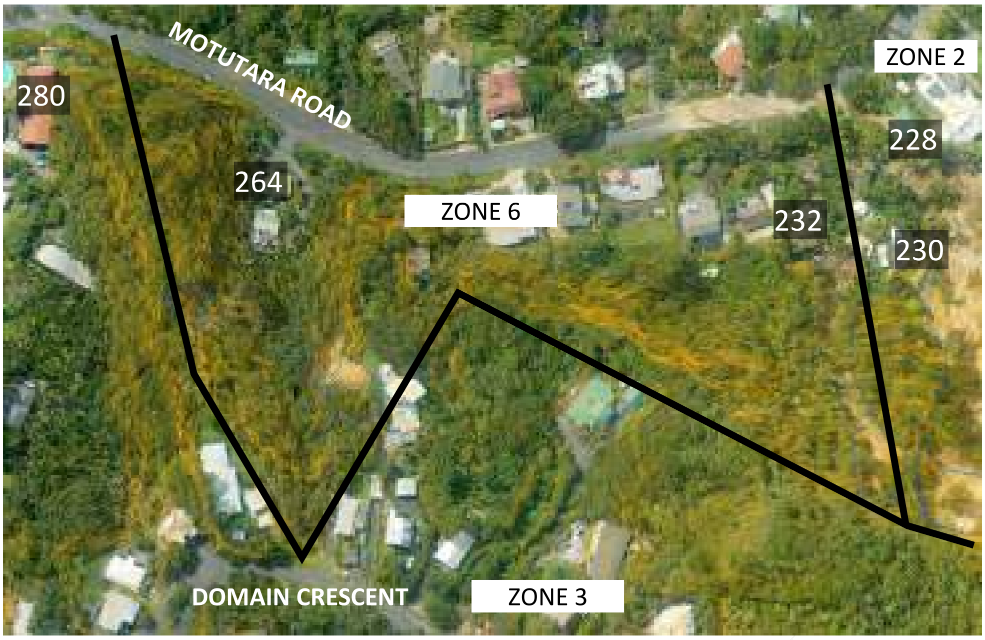


Figure B43 *Location of the Zone 2 / Zone 3 / Zone 6 boundary. North is to the top of the page.*

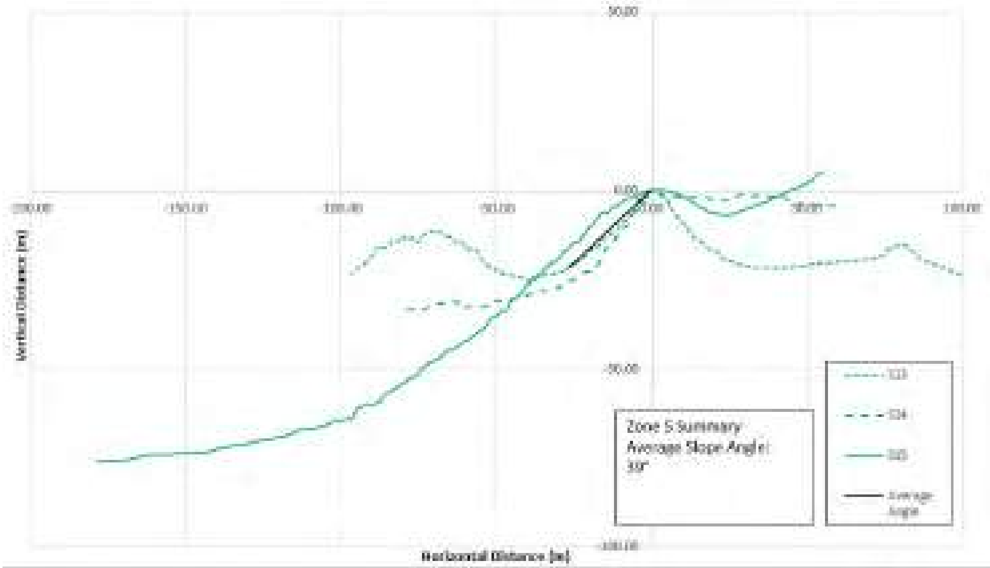


Figure B44 *Slope profile comparison of Zone 6 surface cross sections (see Figure A125 for location of sections)*

B7. Conclusions

The following conclusions are made in relation to the engineering geological assessment of the Muriwai landslide hazard:

1. The recent (2023) and historical (1965) landslides that have affected the Muriwai community were high-velocity debris flows originating on the escarpment that extends up to 80 m above the township.
2. The model proposed for the recent (2023) and historical (1965) landslides that damaged the Muriwai community is that of saturated and shallow translational slips that quickly become high-velocity debris flows, entraining significant volumes of unconsolidated sand and vegetation.
3. The formation of these landslides can be directly attributed to the saturation of surficial soil (colluvium and weathered rock) in the Awhitu Sand Formation which, upon losing its binding iron-cement, develops a shallow shear surface.
4. This process is probably influenced by a combination of surface water infiltration and subsurface pore pressure increases from perched aquifers and associated springs. However, as no groundwater or overland flow data is available from during the events, reliance is placed on anecdotal accounts which do not provide a clear picture.
5. From the data available, including continuous groundwater monitoring established after the 2023 event, it is inferred that surface water flow and infiltration/saturation of shallow soils has had the greater effect on the onset of landslides.
6. The speed, composition, and volume of the debris generated make these debris flows highly destructive to dwellings and property located within the run-out area. As a result, tragically, multiple fatalities were experienced in both the 1965 and 2023 events.
7. The debris flows follow local catchment valleys which often coalesce multiple landslides into confined areas. Consequently, the location and degree of damage to residential properties is variable along Domain Crescent and Motutara Road.
8. Deep-seated landslides resulting from large (i.e. ARI 100 year) rain events within the study area (escarpment) and geology (Awhitu Formation) sand, are not considered likely. Although evidence that may be plausibly attributed to larger historical landslides has been observed, the relative magnitude of these features compared with the 2023 event suggests much larger, less frequent environmental conditions would be required to instigate failure (most likely a very large earthquake). Such conditions and resultant hazards have not been considered for this assessment.
9. Six geomorphological landslide 'zones' have been defined based on the surface topography, 2023 landslide characteristics and general geomorphology of the study area. These differentiate areas according to their susceptibility to large-scale landslides (i.e. having a volume of more than approximately 50 m^3). Zones 2, 3 and 4 contain the Muriwai escarpment and have higher potential for future, large landslides.
10. The life risk to residents for each zone is considered separately in the risk assessment (Appendix E).

B8. Limitations

This report has been prepared by GHD Limited (GHD) for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in Section 1 of this report.

GHD otherwise disclaims responsibility to any person other than Auckland Council arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions and conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on information obtained from, and testing undertaken at or in connection with, specific sample points. Site and ground conditions inferred at other parts of the site may be different from the site conditions found at the specific sample points.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer Section 1 of this report). GHD disclaims liability arising from any of the assumptions being incorrect.

GHD does not accept responsibility arising from, or in connection with, varied conditions and any change in conditions. GHD is also not responsible for updating this report if the conditions change.

An understanding of the geotechnical site conditions depends on the integration of many pieces of information, some regional, some site specific, some structure specific and some experienced based. Hence this report should not be altered, amended, abbreviated, or issued in part in any way without prior written approval by GHD. GHD does not accept liability in connection with the issuing of an unapproved or modified version of this report.

Verification of the geotechnical assumptions and/or model is an integral part of the design process - investigation, construction verification, and performance monitoring. If the revealed ground or groundwater conditions vary from those assumed or described in this report the matter should be referred back to GHD.

B9. References

Technical Literature

Auckland Council (2023). 'Guidelines on the use of AGS (2007) for landslide risk assessment in Auckland following the 2023 flooding and cyclone'. Memorandum dated 20 September 2023.

B. W Hayward (1976): 'Lower Miocene geology and sedimentary history of the Muriwai-Te Waharoa coastline, North Auckland, New Zealand'; New Zealand Journal of Geology and Geophysics, Volume 19, No. 5

B. W Hayward (1979): 'Ancient Undersea Volcanoes: A guide to the geological formations at Muriwai, west Auckland"; Geological Society of New Zealand Guidebook No. 3'

B. W Hayward (2022). The tragic 1965 Muriwai Landslide. Geocene 28: 2-5

Corominas, J. (1996). The angle of reach as a mobility index for small and large landslides. Canadian Geotechnical Journal, Vol 33, pp. 260-271.

D. J.: 'Slope movement types and processes. In Special Report 176: Landslides: Analysis and . Varnes, 1978Control'; TRB National Research Council Washington.

D.M. Cruden & D. J. Varnes (1996): 'Landslide Types and Processes'; Transportation Research Board, U.S. National Academy of Sciences, Special Report, 247: 36-75

Fell R., Ho K.K.S., Lacasse S., Leroi E. (2005). A framework for landslide risk assessment and management. In: Hungr O, Fell R, Couture R, Eberhardt E (eds) Landslide risk management. Taylor & Francis, London, pp 533–541

Finlay P.J.; Mostyn G.R. and Fell R. (1999). Landslides: Prediction of travel distance and guidelines for vulnerability of persons. Proceedings of the 8th Australia New Zealand Conference on Geomechanics, (Vitharana and Colman eds.) Hobart, Australian Geomechanics Society, pp. 105-113.

GHD (2023[1]). Muriwai Resilience Assessment – Stormwater; Private Property Desktop Assessment Report. For Auckland Council. 15 December 2023.

GHD (2023[2]). Muriwai Resilience Assessment – Stormwater; Oaia Road and Edwin Mitchelson Track Investigation Report. For Auckland Council. 18 December 2023.

Heim, A. (1932). Landslides and human lives (Bergstruz and Menchen leben). Translated by N. Skermer. BiTech Publishers, Vancouver, B.C., 195 p

Hsu, K.J. (1975). Catastrophic debris streams (sturzstroms) generated by rockfalls. Geological Society of America Bulletin, Vol 86, pp. 129-140.

Hungr, O., Leroueil, S. and Picarelli, L. (2014). The Varnes Classification of Landslide Types, an Update. Landslides (2014) 11:167–194

Hungr. O.; Corominas, J. and Eberhardt, E. (2005). Estimating landslide motion mechanisms, travel distance and velocity. In Landslide Risk Management Editors. O. Hungr, R. Fell, R. Couture and E. Eberhardt. Taylor and Francis, London. 99-128.

Hunter, G. & Fell, R. (2003). Travel distance angle for rapid landslides in constructed and natural soil slopes. Canadian Geotechnical Journal 40(6): 1123-1141.

Hunter. A., Flentje, F. and Moon. A. (2022). Bulli Pass Landslide Risk Management Part 1. Australian Geomechanics, Vol 57, No3.

Hunter. G., & Fell. R. (2002). Estimation of Travel Distance for Landslides in Soil Slopes. Australian Geomechanics, Vol 37, No2.

J. C. Schofield, 1975: 'Sea-level fluctuations cause periodic, post-glacial progradation, South Kaipara Barrier, North Island, New Zealand'; New Zealand Journal of Geology and Geophysics, Volume 18, No. 2

L. W. Wright, 1966: 'The Muriwai Debris-Avalanche: Some Aspects of Its form and Genesis'; New Zealand Geographer

Moon A.T., Wilson R.A. and Flentje P.N. (2005). Developing and using landslide size frequency models. In: Hungr O, Fell R, Couture R and Eberhardt, E (eds) Landslide Risk Management, CRC Press, pp 681-690.

P.R. Goldsmith & E.H Smith, 1984: "Tunnelling soils in South Auckland, New Zealand"; Fourth Australia – New Zealand Conference on geomechanics, Perth, 14-18 May 1984

Rodney District Council, 2005: "Muriwai Community Plan"; Strategy and Policy

Scheidegger, A.E. (1973) On the prediction of the reach and velocity of catastrophic landslides. Rock Mechanics, Vol 5, pp. 231-236.

Smith, D. and Hungr, O. (1992) Failure behaviour of large rockslides – Report to the Geological Survey of Canada and BC Hydro and Power Authority. Report No. 16-11-6, Thurber Engineering Ltd.

Public Articles

Interest New Zealand. Brooke, 21 Feb 2023, from Learning the lessons from landslides | interest.co.nz

Paper Past New Zealand. 1965. Papers Past | Newspapers | Press | 2 September 1965 | Mopping Up After Slips (natlib.govt.nz) PRESS, VOLUME CIV, ISSUE 30845, 2 SEPTEMBER 1965, PAGE 3

Stuff New Zealand. 15 Aug 2013, from Old memories revisited | Stuff.co.nz

Auckland Star. 20 June 1934. Papers Past | Newspapers | Auckland Star | 20 June 1934 | THE DELUGE. (natlib.govt.nz) AUCKLAND STAR, VOLUME LXV, ISSUE 144, 20 JUNE 1934, PAGE 9

Manawatu Standard. 27 Dec 1926. Papers Past | Newspapers | Manawatu Standard | 27 December 1926 | FLOODS IN THE NORTH. (natlib.govt.nz) MANAWATU STANDARD, VOLUME XLVII, ISSUE 24, 27 DECEMBER 1926, PAGE 8

Evening Star. 27 Dec 1926. Papers Past | Newspapers | Evening Star | 27 December 1926 | RECORD FLOOD (natlib.govt.nz) EVENING STAR, ISSUE 19441, 27 DECEMBER 1926, PAGE 7

Wairarapa Daily Times. 1926. Papers Past | Newspapers | Wairarapa Daily Times | 28 December 1926 | UNSEASONABLE WEATHER. (natlib.govt.nz) WAIRARAPA DAILY TIMES, 28 DECEMBER 1926, PAGE 5

Southland Times. 28 Dec 1926. Papers Past | Newspapers | Southland Times | 28 December 1926 | AUCKLAND'S RAIN (natlib.govt.nz) SOUTHLAND TIMES, ISSUE 20063, 28 DECEMBER 1926, PAGE 7

Christchurch Star. 27 Dec 1926. Papers Past | Newspapers | Star (Christchurch) | 27 December 1926 | The Worst Floods For Fifty Years Do Damage In... (natlib.govt.nz) STAR (CHRISTCHURCH), ISSUE 18039, 27 DECEMBER 1926, PAGE 7

Evening Post, 28 Dec 1922. Papers Past | Newspapers | Evening Post | 28 December 1922 | HEAVY FLOODS (natlib.govt.nz) EVENING POST, VOLUME CIV, ISSUE 154, 28 DECEMBER 1922, PAGE 7

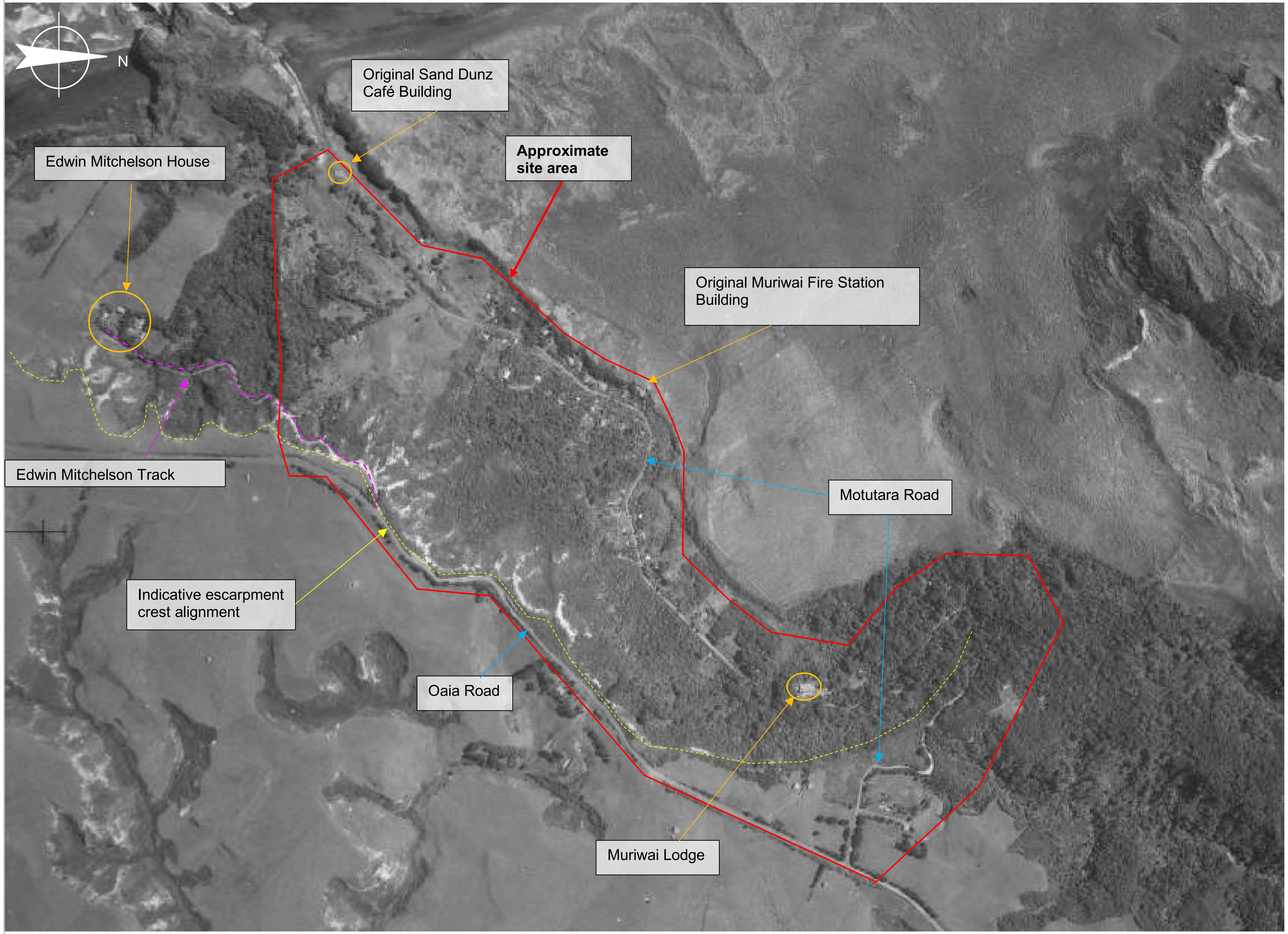
Manawatu Times. 29 Dec 1922. Papers Past | Newspapers | Manawatu Times | 29 December 1922 | HEAVY FLOODS. (natlib.govt.nz) MANAWATU TIMES, VOLUME XLVI, ISSUE 2536, 29 DECEMBER 1922, PAGE 5

Appendices

Appendix B-1

Historical air photograph record

Historical aerial photography

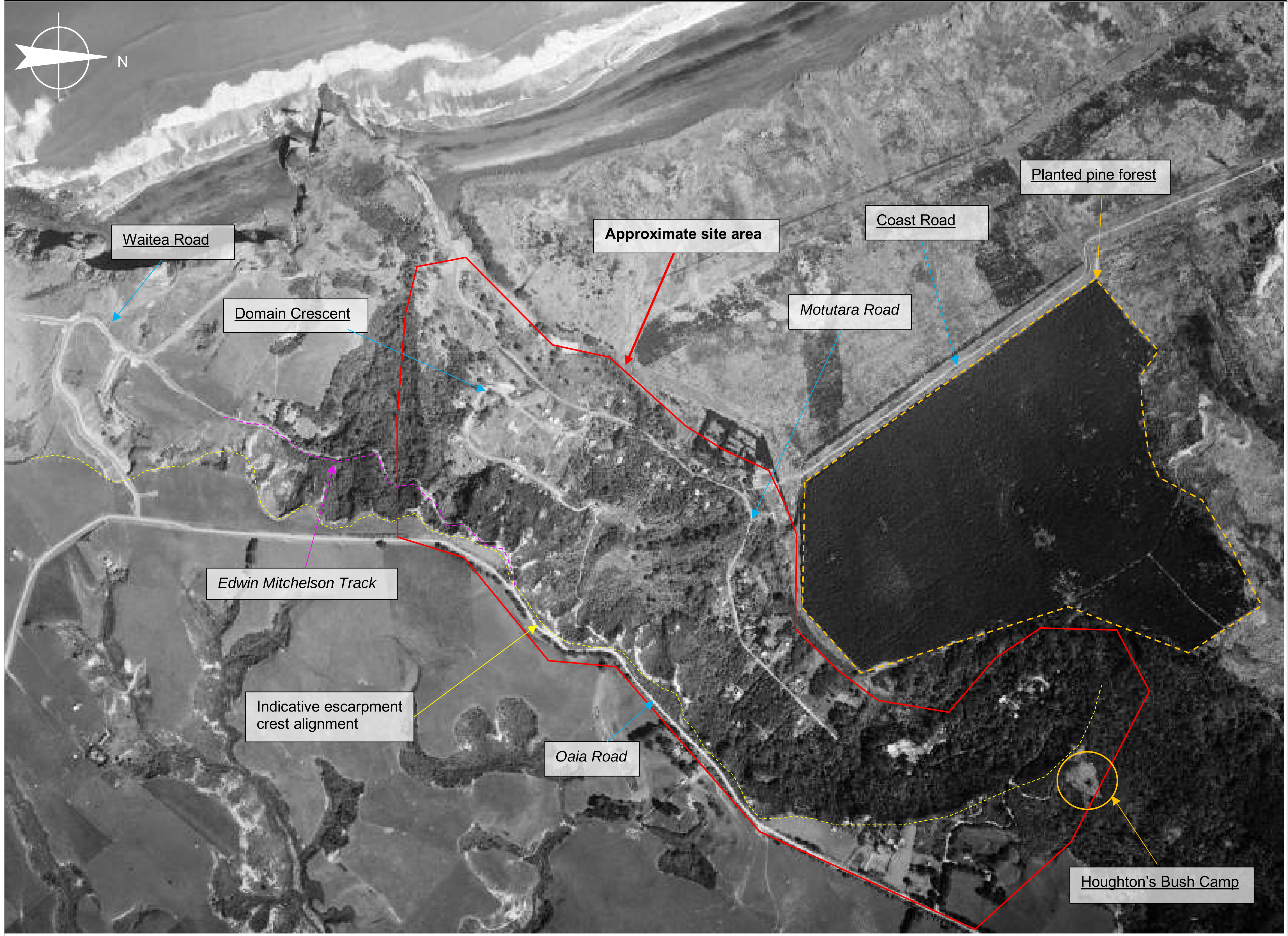


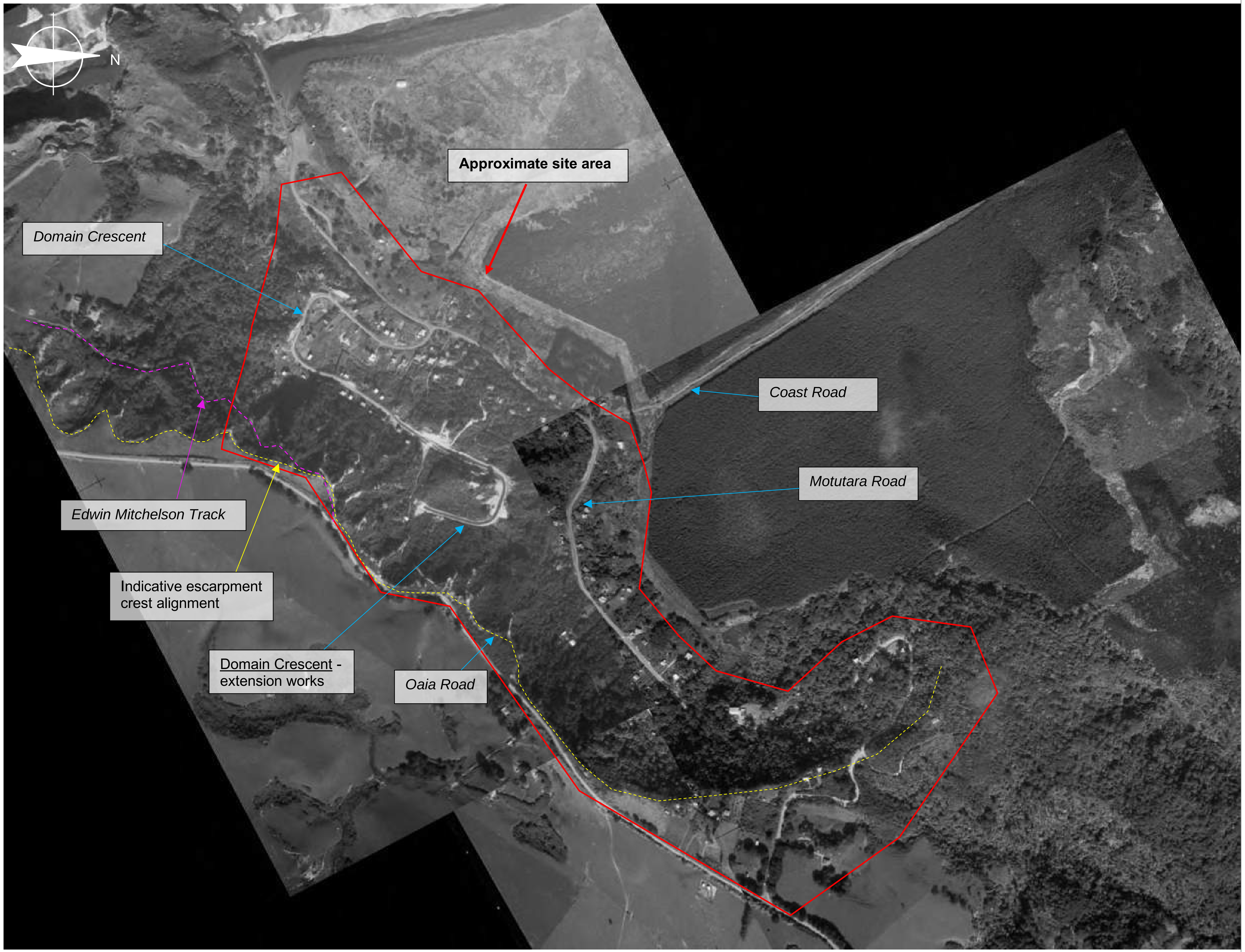
Comments

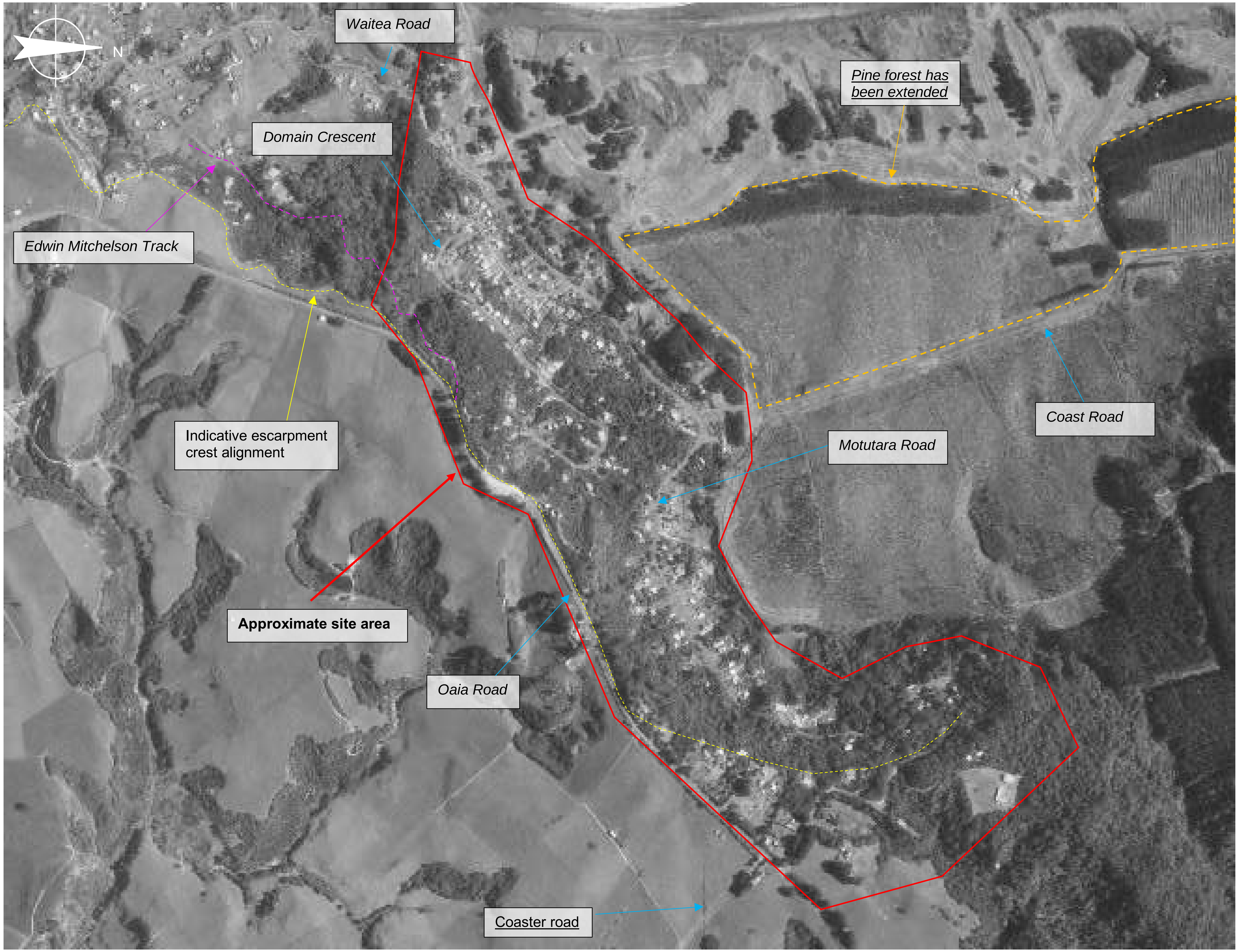
Source: Retrolens
Date: 22/04/1940
Original Scale: 1:16,000
Survey No : SN143
Run #: 93
Photo Number #: 3

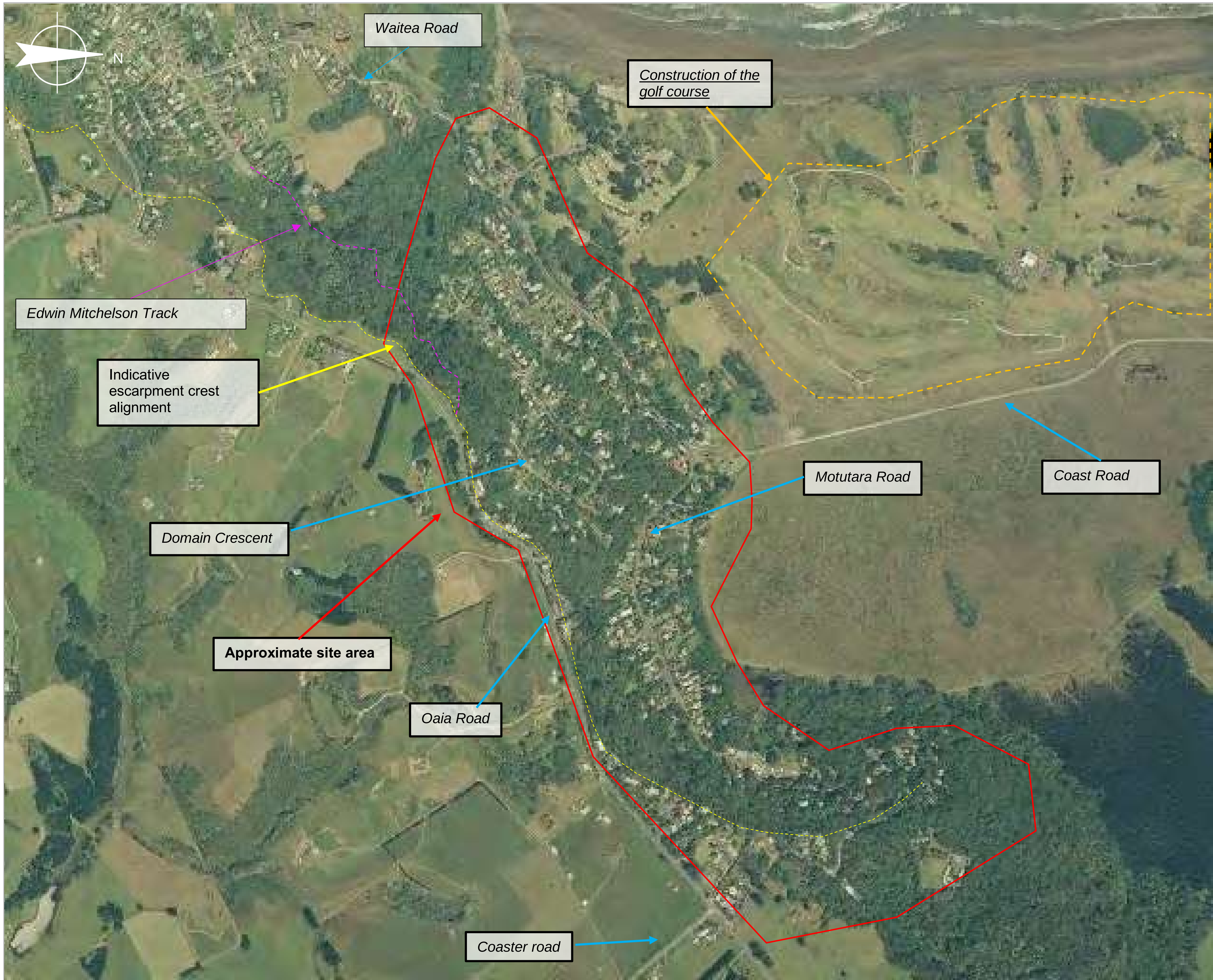
Summary of site conditions

- Crest of escarpment clearly visible to immediate west of Oaia Road and extending further south.
- Oaia Road does not extend past Edwin Mitchelson Track.
- Edwin Mitchelson Track forms the driveway to Edwin Mitchelson House.
- Motutara Road has been constructed.
- Very little property development has been undertaken. Several buildings are still present today.
- The southern extent of Muriwai (accessed from Waitea Road) is undeveloped.
- Vegetation (scrub and low bush) extends over most of the project site.
- Erosional "scaring" below escarpment visible.

Historical aerial photography	Comments
	**Source: Retrolens** **Date: <u>19/09/1950</u>** **Original Scale: 1:15,900** **Survey No #: SN583** **Run #: 1916** **Photo Number #: 3** **<u>Summary of key land use change:</u>** - Increase in property development, as well as the development of Houghton's Bush Camp. - Forest/vegetation development north of the site - Development of Domain Crescent has begun. - Part of Waitea Road has been constructed. - Coast road has been developed from Motutara Road. - Pine forest has been planted adjacent to Motutara Road and Coast Road.

Historical aerial photography	Comments
	**Source: Retrolens** **Date: 22/10/1953** **Original Scale: 1:8,400** **Survey No #: SN832** **Western end:** **Run #: D** **Photo Number #: 34** **Northeastern end:** **Run #: C** **Photo Number #: 32** **Southeastern end:** **Run #: C** **Photo Number #: 33** **Summary of key land use change:** - Domain Crescent has been extended to present day location. Associated minor residential development.

Historical aerial photography	Comments
	**Source: Retrolens** **Date: 31/07/1975** **Original Scale: 1:49,000** **Survey No #: SN3800** **Run #: B** **Photo Number #: 3** **Summary of key land use change:** - Two landslides occurred in 1965 between the Edwin Mitchelson track (which is located along the escarpment) and Domain crescent due to blocked water table. - Further property development within the site. Most prominently along Motutara Road. - The current Muriwai Fire Station facility has been established as of 1965. - Waitea Road has been extended and now intersects Motutara Road. - Pine forest has been extended to the west of Coast Road.

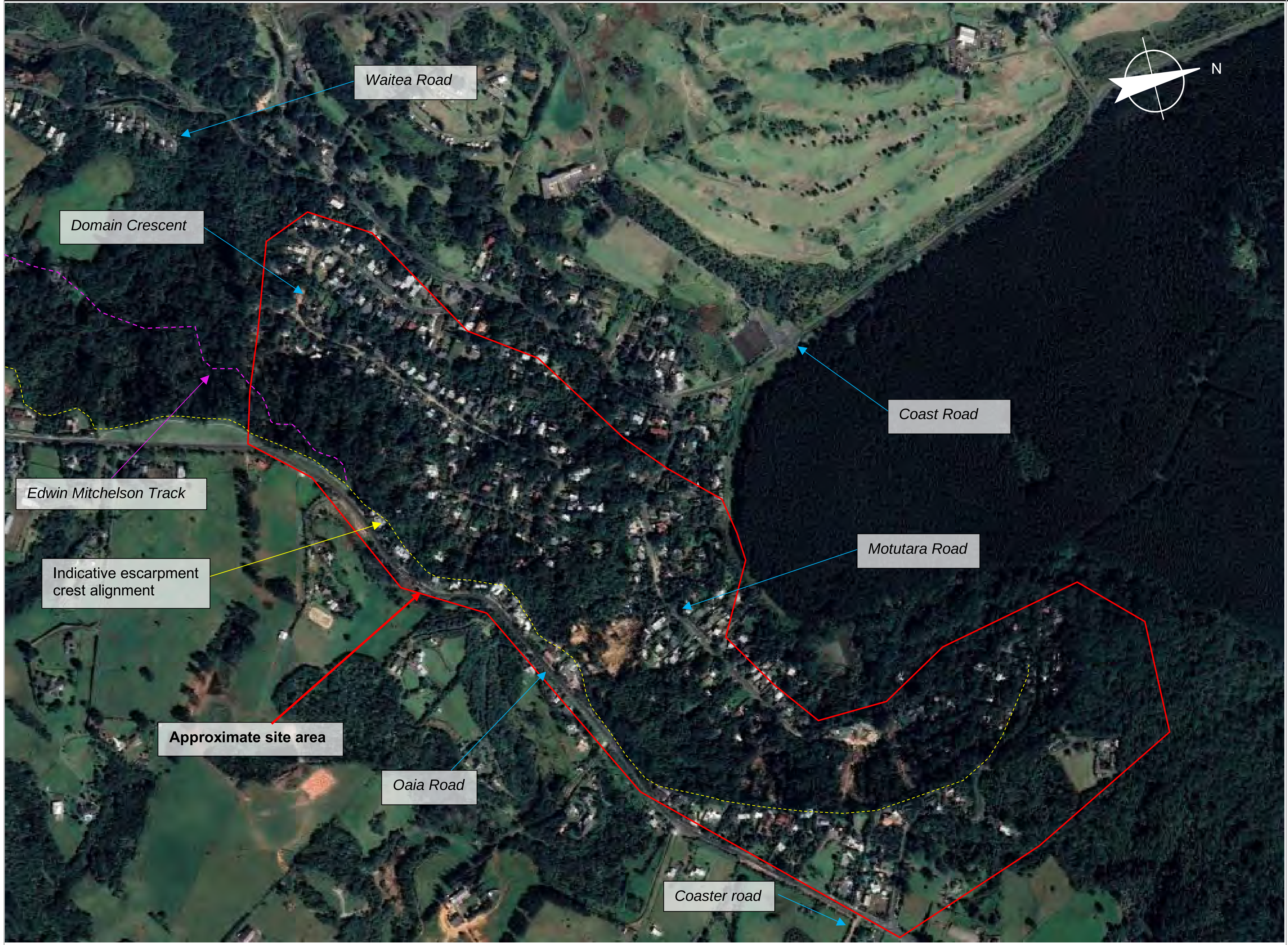


Source: Retrolens
Date: 02/01/2004
Original Scale: 1:49,000
Survey No #: SN3800
Run #: B
Photo Number #: 3

Summary of key land use change:

- The pine forest, west of Coast Road has been removed and the golf course has been constructed.
- Increased density of residential housing.

Historical aerial photography	Comments
	**Source: GeoMaps** **Date: 2015-2016** **Summary of key land use change:** - Property development within Domain Crescent. - Minor building constructions outside of the site such as the Muriwai Surf Club and Tennis Courts. - The current business named “The Samd Dunz Beach Café” is registered as of 23 Oct 2014

Historical aerial photography	Comments
	**Source: Google Earth** **Date: March 2023** **<u>Summary of key land use change:</u>** - Recent landsliding visible from satellite imagery. - Pine forest and vegetation along the escarpment is well established.

Appendix B-2

Summary of anecdotal evidence

Information relating to the vicinity of Domain Crescent:

- Noted that individual slopes have not experienced any slope failure or topsoil slips, including from people who have been residents since 1975.
- A small landslip occurred in 2000 on the east side of 60 Domain Crescent. A retaining wall was subsequently constructed in 2006 as part of a dwelling construction.
- The southern area of Domain Crescent below the escarpment (approximate house numbers 51 to 65) was swampy in 1981. In the same area above the dwellings, slope debris has been observed, as have downhill-leaning trees.
- Following February 2023, water seepage has been observed from areas not previously known to have seeped, e.g. in cracks in paved surfaces.
- Numerous seepage points have been noted at the uppermost, eastern end of Domain Crescent on the slope below the escarpment (approximate house numbers 124 to 131). An array of open drains has been installed, most recently in 2018 by Auckland Council. Swampy, saturated ground was noted in areas that subsequently failed in February 2023.
- Reference has been made to the Park Rangers asking local people to clear drains on public land below the escarpment in the 1970s and 1980s.
- Open drains frequently blocked by leaf litter. Some were flowing prior to Cyclone Gabrielle.

Information relating to the vicinity of the escarpment at Oaia Road and north Motutara Road:

- Small, localised landslip below escarpment at north Motutara Road following a 2021 storm.
- Numerous springs within the escarpment at north Motutara Road.
- Some reports of water reticulation pipework directed over the top of the escarpment from Oaia Road properties towards Muriwai. In addition, blockages of public stormwater sumps with vegetation has been observed.
- Tree-fall from was observed from February 2023 storm damage. Some downhill-leaning trees have been observed.

Information relating to the vicinity below the escarpment at Motutara Road.

- In January a small slip was observed on the road below 112 Motutara Road and one further uphill in the bush.
- Mature trees that lean downslope have been observed. Some of these have been felled by homeowners.
- Swampy ground observed at toe of slope on the eastern site of Motutara Road. Some small-scale slips have also been observed in this area.
- Surface water flow east of Motutura Road has been observed with increasing volume from January and February 2023. In some cases these discharge from below buildings and have entrained sediment.
- A spring was observed on the western (downhill) side of Motutara Road.
- In the late 1990s, a stream was observed from Domain Crescent through to 302 Motutara Road. This was later remediated by Auckland Council. A slip was observed on the side of Motutara Road.
- Blocked open drains have been observed. Residents sometimes clear these.
- Stormwater infrastructure was observed to be overwhelmed by February 2023 stormwater flows.
- Localised flooding observed in frequent occurrence (i.e. relatively small) storm events.

We conclude the following from the anecdotal evidence:

- Below the escarpment there are numerous springs and saturated, swampy areas.
- Surface water control has been necessary with open drains for a long period of time. In some cases these have not been maintained, or have been overwhelmed by storm flows, particularly in early 2023.
- There have been numerous indications of shallow slope instability, such as leaning trees or small-scale slips.
- There are no anecdotal reports of large landslides having affected the area between 1965 and 2023, in addition to the published events.

Appendix B-3

Summary of reviewed literature

Source/subject	Summary of key points relevant to this assessment
Wright (1966). Engineering geological review of 1965 Muriwai landslides.	- A severe storm in August 1965 resulted in approximately 200 mm of rain and, two large landslides above Domain Crescent that caused destruction of a house and two fatalities. - Anecdotal evidence suggests the landslide moved as a high velocity, saturated debris flow. Discussion and field observations suggest initial movement of an intact block before near-instantons break down to a liquefied debris flow. - The depth of the slip plane was estimated between approximately 0.5 m and 2.0 m. - Face-seepage of groundwater was observed at mid-slope along the landslide (extending for several days after) and concentrated along bedding plane outcrops with siltstone-sandstone. These may have contributed to the landslide.
Interest NZ (2023) Landslides and law: Cyclone Gabrielle raises serious questions about where we've been allowed to build	- 1965 landslide above Domain Crescent in Muriwai
Press (1965) Mopping up After slips	- 1965 landslide above Domain Crescent
Rodney District Council (2005). Muriwai future planning document dealing with a wide range of considerations including environmental hazard.	- Addresses the implications of the built environment having a negative impact on slope stability natural hazard at Muriwai: removal of stabilising vegetation to support residential growth; addition of low permeability surfaces that increases run off and erosion; lack of reticulated wastewater system, increases ground saturation through septic-systems. - Recommended most of the area below the escarpment and on the escarpment be avoided for construction of residential dwellings without prior geotechnical assessment. - Outlines that the township in its current location is vulnerable to slope stability hazard. - Notes the history of road-side failure/ drop-outs on Domain Crescent - Notes multiple areas of surface stormwater ponding, which are primarily concentrated at the immediate base of the escarpment slope, overlain with residential properties built off Domain Crescent and Motutara Road
Hayward (2022). Summary of 1965 landslip event with focus on two Domain Crescent slips and additional commentary to Wright, 1966.	- Draws additional focus to the mechanism of the 1965 landslide failure; concludes it likely the result of both groundwater surface springs from geological unconformity (per Wright, 1965) but in addition, direct surface saturation near the headscarp from surface flows over-topping the Edwin Mitchelson Track. - Notes that Rodney District Council stated no further development in the area destroyed (surrounding 51-53 Domain Crecent); however, notes that in present day, this has not been adhered too with multiple new dwellings.
Auckland Council (2023). Summary of measured and inferred rainfall accumulation at Muriwai during Cyclone Gabrielle. Reference reproduced in Appendix E.	- Outlines that rainfall in Muriwai was measured via direct rain gauge (tipping bucket 'TP08') however this failed at 1am 14 February due to flooding damage. In addition to this record, a Quantitative Precipitation Estimate was taken, which estimates rainfall intensity and accumulation from rainfall radar data.

	- Data indicates over 130 mm of rain fell at Muriwai over a 12-hour period from 13-14 February. In total, over 180 mm was estimated to accumulate over the Cyclone Gabrielle event. - The recorded figures above exceed the 100-year event return period for a 12-hour duration. - The total rainfall that had been recorded over January (including Cyclone Hale) was approximately seven times the normal accumulated amount for this month in this location (490 mm recorded, compared with 70 mm for normal).
Stuff (2013) Old memories revisited	- 2013 landslide above Domain Crescent in Muriwai
Auckland Star (1934) The deluge. Many floods. Traffic delay.	- 1934 flooding observed of the creek close to Muriwai beach causing a relief workers' camp to flood
Manawatu Standard (1926) Floods in the North. A record rainfall in Waitakere Ranges. Campers in peril at Muriwai	- 1926 flooding observed in Muriwai. A few buildings were flooded and displaced at Motutara Domain. The road approach the beach was washed away, and the campground became untenable.
Evening Star (1926) Record flood. Auckland cloud bursts eight inches of rain in a day.	
Wairarapa Daily Times (1926) Unseasonable weather. Floods in the North.	
Southland Times (1926) Auckland's rain phenomenal fall. The worst for fifty years.	
Christchurch Star (1926) The worst floods for fifty years do damage in North.	
Evening Post (1922) Heavy floods. Auckland trippers caught. [10]	- 1922 flooding cut off traffic access to Muriwai.
Manawatu Times. 29 Dec 1922. Heavy floods. Auckland trippers caught. [11]	

Appendix B-4

Database of observed 2023 landslides

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 2	M-LS01	Translational, Debris flow	1728500.19	5924036.28	36	0.5	142	38	Large landslide has damaged or destroyed multiple structures on multiple properties. A patch of insitu trees is visible.	
	M-LS02	Translational, Debris flow	1728523.55	5923935.03	52	0.5	127	31	Large landslide has damaged or destroyed multiple structures on multiple properties. Landslide debris comprises Awhitu Sand. Patch of Insitu palm trees present within the centre of the landslide	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 2	M-LS03	Translational, Debris flow	1728528.85	5923806.37	33	0.25	91	42	Large landslide above Watercare's water treatment plant on Motutara Road	
	M-LS04A	Translational, Debris flow	1728515.77	5923775.84	26	0.75	116	47	Large landslide with strip of intacted trees down the middle. Spring daylighting near the base of escarpment	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 2	M-LS04B	Translational, Debris flow	1728510.78	5923749.67	27	0.75	151	41	Large landslide with strip of intacted trees down the middle. Spring daylighting near the base of escarpment	
	M-LS05 does not exist. Next landlside is M-LS06									
	M-LS06	Translational, Debris flow	1728361.87	5923509.18	15	0.25	120	27	Three distinct landslides. Spring located towards the base of the slope. A darker confining layer is present below the spring.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 2	M-LS07	Translational, Debris flow	1728341	5923497.96	16	0.25	10	31	Three distinct landslides. Spring located towards the base of the slope. A darker confining layer is present below the spring.	
	M-LS08	Translational, Debris flow	1728314.83	5923503.88	27	0.25	108	40		

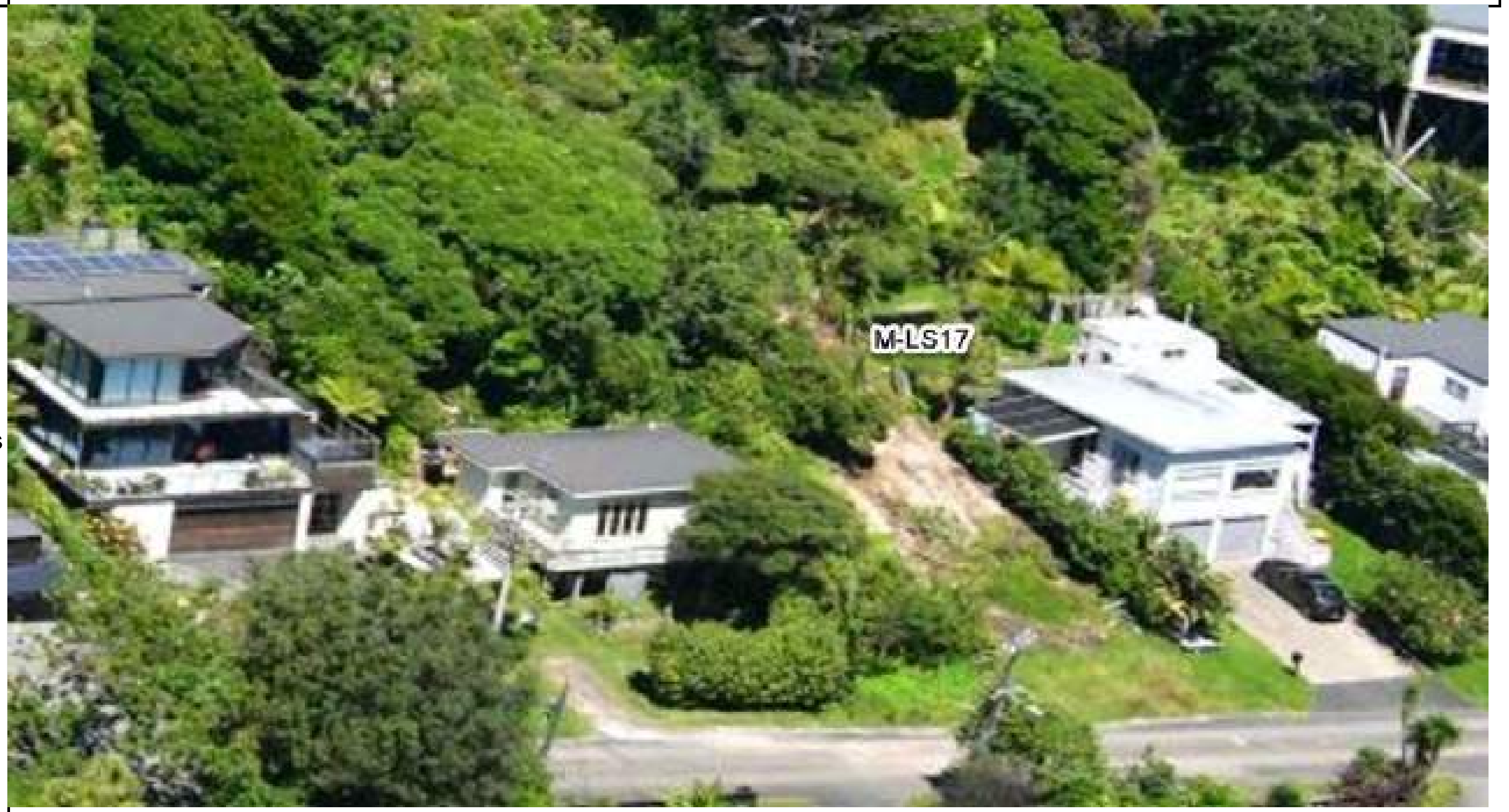
Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 2	M-LS09	Translational, Debris flow	1728261.56	5923470.24	77	0.75	154	31	Large landslide with amalgamated debris flow at base. Debris comprises Awhitu Sand and vegetation. No observed spring feature, however water was observed on the face of a darker confining layer close to the invert of the base of the slope.	
	M-LS31 and M-LS32 do not exist. Next landslide is M-LS33									
	M-LS33	Translational, Debris flow	1728339.44	5923575.22	8	0.25	26	44	Smaller landslide occurred within dense vegetation, located near the base of the escarpment	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 2	M-LS34	Translational, Debris flow	1728294.58	5923514.47	19	0.25	63	48	A separate landslide downslope of the main escarpment. Two confining ridgelines form the headscarp.	
	M-LS43	Translational, Debris flow	1728425.33	5923631.56	9	1	30	35	Smaller landslide occurred within dense vegetation, located near the base of the escarpment	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS11	Translational, Debris flow	1728087.884	5923389.317	15	0.5	47	25	Landslide has occurred within the cut slope above the driveway.	
	M-LS12	Translational, Debris flow	1728130.018	5923292.121	8	0.5	89	38	A confining layer is present towards the base of the depletion zone with a small spring located above it. The landslide is located on the mid-slope of the escarpment.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS13	Translational, Debris flow	1728038.624	5923223.157	9	0.5	58	28	Cross bedded Awhitu Sand visible in head scarp. Seepage originating from cross bedding is visible. Dark bluish grey clayey material observed 2 m below head scarp.	
	M-LS14	Translational, Debris flow	1728006.382	5923218.951	20	0.5	71	26	Landslide has occurred along a dark bluish grey silty / clayey material. Thickness of this unit in this location is approx. 8 m.	

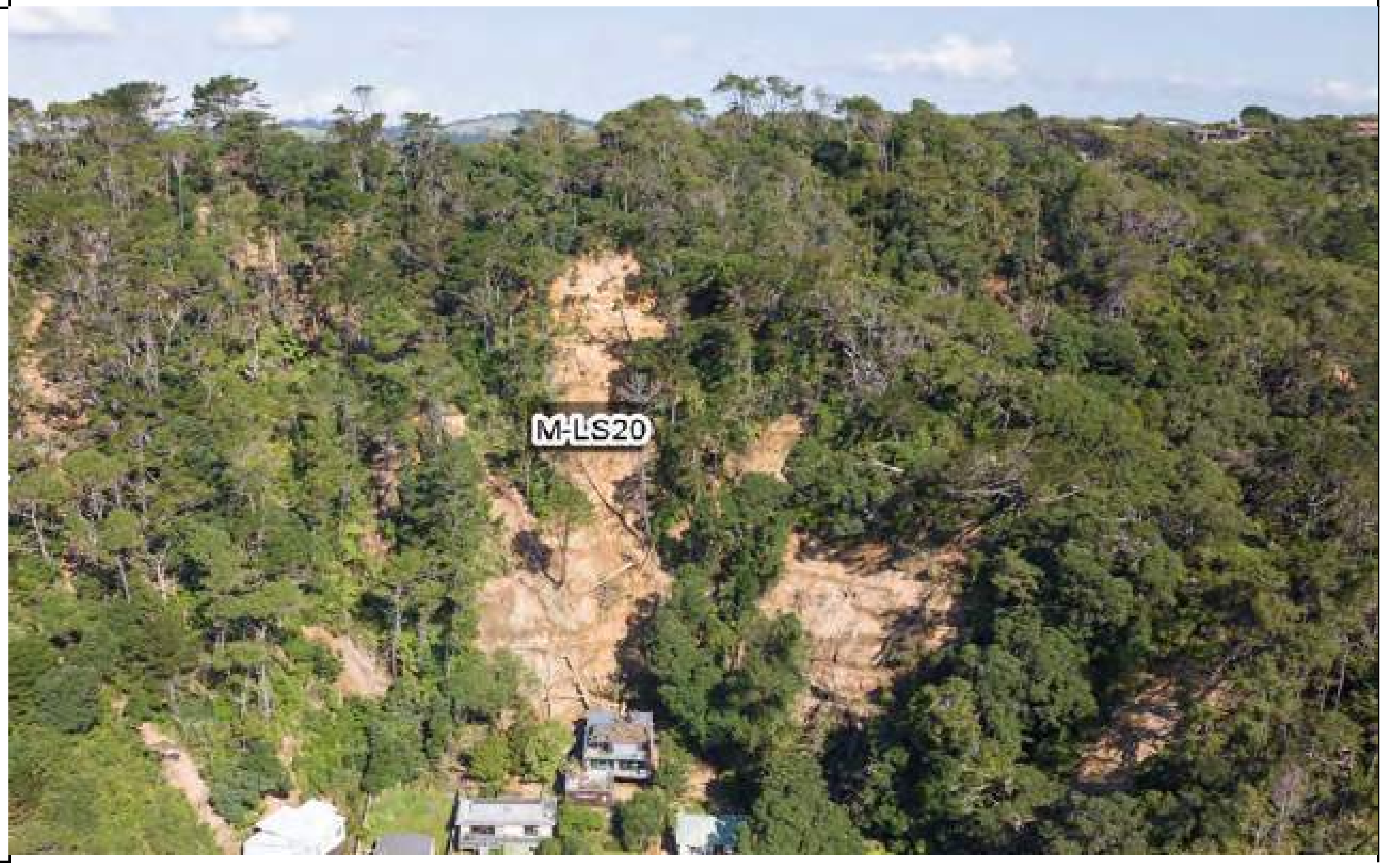
Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS15	Translational, Debris flow	1727964.793	5923202.596	15	0.5	47	43	Landslide is located on the mid-slope of the escarpment to the south of the dwelling at 131 Domain Crescent.	
	M-LS16	Translational, Debris flow	1727985.431	5923129.154	19	1	45	27	Intact culvert protruding from the headscarp. Landslide located downslope of the Edwin Mitchelson Track cut (underslip). Middle of slip has been scoured by culvert outlet	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS17	Translational, Debris flow	1727833.251	5923147.612	6	0.5	23	31	Landslide located within the vacant lot. Slip face observes a blocky texture indicating possible block failure manifesting as a debris flow.	
	M-LS18A	Translational, Debris flow	1727924.372	5923021.288	13	0.25	18	55	Landslide has occurred within the upslope cut of the Edwin Mitchelson track (overslip). Track remains mostly intact with some debris on the track.	

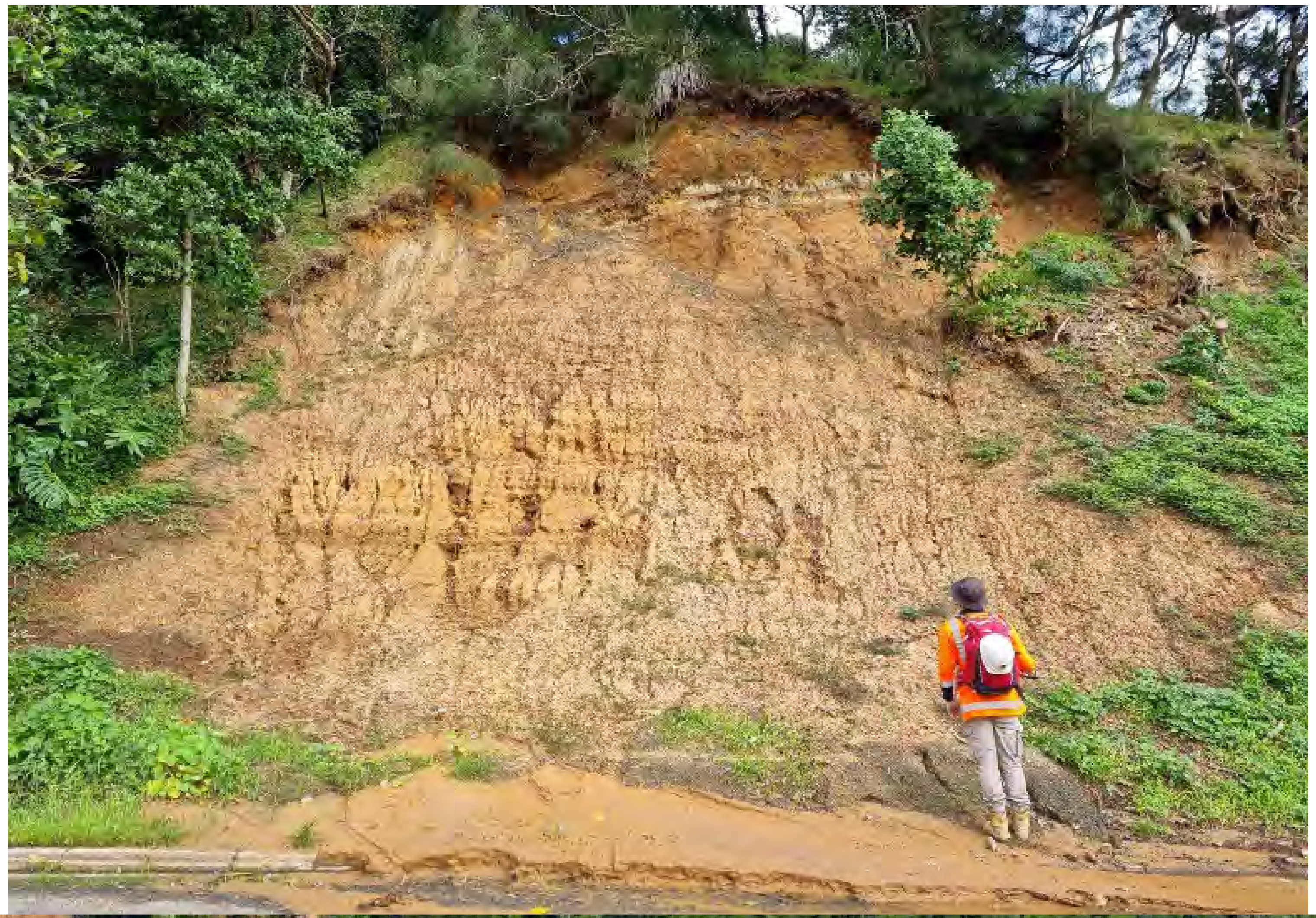
Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS18B	Translational, Debris flow	1727906.46	5923033.905	38	0.5	132	37	Landslide has occurred as an underslip below the Edwin Mitchelson Track. along walking track.	
	M-LS30	Translational, Debris flow	1728143.531	5923377.985	7	0.5	14	46	Small headscarp located behind dwelling at 114 Domain Crescent. Debris locally arrested by house.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS35	Translational, Debris flow	1727947.192	5923160.384	23	0.5	81	39	Inaccessible by foot - mapping was caried out using aerial photography.	
	M-LS36 to M-LS40 do no exist. Next landlside is M-LS41									
	M-LS41	Translational, Debris flow	1727953.227	5923371.054	14	1	8	55	Landslide has occurred as an overslip within the road cut of Domain Crescent.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 3	M-LS42	Translational, Debris flow	1727907.628	5923229.037	4	1	25	40	A landslide has occurred behind and upslope of the dwelling. The landslide has occurred on the slopes toward the lower base of the escarpment.	
Zone 4	M-LS19A	Translational, Debris flow	1727917.791	5922983.788	49	0.5	25	55	Landslide has occurred within the upslope cut of the Edwin Mitchelson track (overslip). Track remains mostly intact with some debris on the track.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 4	M-LS19B	Translational, Debris flow	1727875.58	5922999.209	38	0.25	115	27	Landslide has occurred as an underslip adjacent to the Edwin Mitchelson track cut. Seepage observed above limonite layers	
	M-LS20A	Translational, Debris flow	1727848.788	5922938.305	46	0.5	13	55	Landslide has occurred within the upslope cut of the Edwin Mitchelson track (overslip). Track remains mostly intact with some debris on the track.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 4	M-LS20B	Translational, Debris flow	1727820.128	5922964.941	96	0.75	137	42	Landslide has occurred as an underslip adjacent to the Edwin Mitchelson track cut. Seepage observed above limonite layers	
	M-LS21	Translational, Debris flow	1727721.219	5922970.237	18	0.25	57	49	Landslide has occured within the slopes behine the dwelling. Relatively shallow failure of residual soil with some of the underlying intact blocks of cemented sand. Approx. 1m thick. Debris very close to slope base, arrested by house on property 47. scarp exposes a 2 m thick bed of white siltys and, with slight NW dip.	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
			Easting (m)	Northing (m)	Approx. Main Scarp Width (m)	Approx. Average Depletion Zone Depth (m)	Approx. Debris Runnout Length (m)	Approx. Local Slope Angle (Degrees)		
Zone 4	M-LS22	Translational, Debris flow	1727698.555	5923022.184	23	0.25	17	53	Landslide has occurred as an overslip within the road cut for Domain Crescent. Relatively shallow <1m depth. Visible cross bedding in 10 cm horizons. finer grained/massive texture.	
Zone 5	M-LS23	Zone 4	1727675.035	5922958.321	40	0.5	30	49	Landslide has occurred within the slopes behind the dwelling. Headscarp is located along the confining local ridgeline	

Geomorphology Zone	Landslide ID	Landslide Mechanism, Type	Coordinates (NZTM)		Landslide Dimensional Data				General Landslide Information	Photographs
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Zone 5	M-LS24	Translational, Debris flow	1727573.789	5922959.879	12	0.25	39	32	Landslide within Awhitu Sand has displaced minimal soil and mostly comprises vegetation. Significant scour observed within the escarpment.	
	M-LS25	Translational, Debris flow	1727554.474	5922953.181	8	0.25	42	31	Landslide was not physically accessible, as such was mapped using aerial photography and lidar.	

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Zone 5	M-LS26	Translational, Debris flow	1727561.406	5923078.92	8	0.51	9	39		
Zone 6	M-LS10	Translational, Debris flow	1728207.043	5923480.828	19	0.25	52	37	Groundwater seeping out of escarpment in multiple locations. Less cemented sand present for most of slip. The landslide has manifested as a debris flow and impacted the dwelling at 232 & 230 Motutara Road	

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Zone 6	M-LS27	Translational, Debris flow	1728026.436	5923507.502	19	0.25	35	26	White silty fine white sand exposed. An open watercourse is present at the base of the gully	
	M-LS28	Translational, Debris flow	1727970.984	5923538.966	11	0.5	20	31	Landslide has occurred off a spur off the main escarpment	

Appendix B-5

Survey data used for GHD analysis and plans

The survey data used by GHD for data presentation and modelling used the following datasets:

- 2016 LiDAR elevation model (Muriwai_dtm_2016)
    - Source: Auckland Council
    - Point cloud accuracy is vertical <= 0.10 m RMS and horizontal <= 0.30 m RMS
- 2016-2018 LINZ DEM (Auckland North LiDAR 1 m DEM)
    - Source: **Auckland North LiDAR 1m DEM (2016-2018) | LINZ Data Service**[4]
    - Vertical Accuracy Specification is +/- 0.2m (95%), Horizontal Accuracy Specification is +/- 0.6m (95%).
- 2023 Muriwai elevation model (Muriwai_dtm_20230304_calibrated_internal).
    - Source: Auckland Council
    - Metadata: **Specified Auckland Areas Post Cyclone LiDAR Point Cloud | Auckland Council Open Data (arcgis.com)**[5]

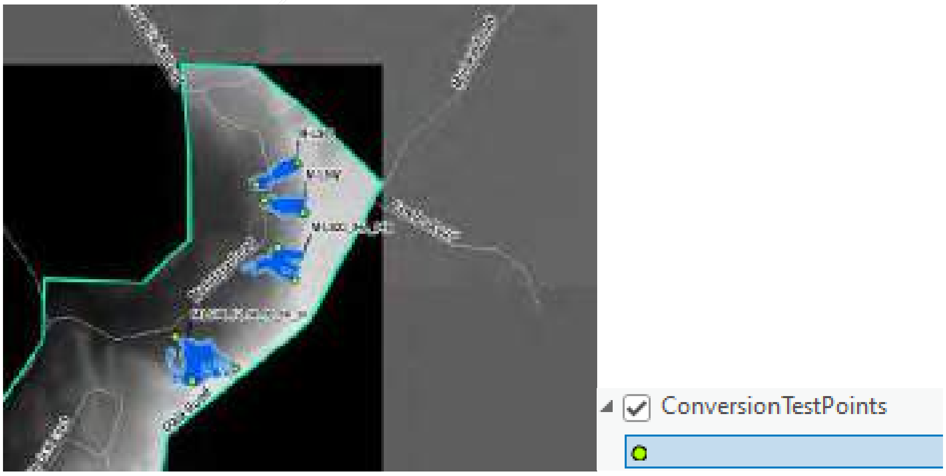
The 2023 Muriwai DTM does not state the vertical datum in the metadata. However, AC have advised the DEM was in NZVD2016 vertical datum.

The 2016 elevation DTM did not have a vertical datum attributed, however the AAM metadata for the 2016-2017 Auckland Council LiDAR data collection mentioned that all products are supplied in Auckland 1946 vertical datum and point cloud products are also supplied in NZVD2016 vertical datum.

As the 2023 elevation data was stated as being in NZVD 2016 and the Auckland DEM from LINZ has metadata stating it to be in NZVD2016 the 2016 DEM from LINZ was selected for raster calculations.

A sample set of 9 points across the landslide areas was created to cross check for differences in elevation. It was noted across this sample set that the Muriwai_dtm_2016 was showing elevation values that were consistently 0.29 m (2 dp) greater than the elevation value off the LINZ DEM confirming that it was in Auckland 1946.

A further check of the 9 sample points by using the LINZ online converter (**New Zealand Vertical Datum Conversions (linz.govt.nz)**) to convert the Muriwai_dtm_2016 elevation values at those sample points to NZVD 2016 using the online converter and comparing them to the values in the LINZ DEM. The average difference was 0.001 (3 dp). This indicated that substituting the LINZ DEM in lieu of converting the Muriwai_dtm_2016 was not going to result in any elevation differences that was likely to affect our interpretations of raster calculations. Also noting this calculated average difference was much smaller than the vertical accuracies stated for the LINZ DEM (+/-0.2m) and Muriwai_dtm_2016 (<=0.1 m).



[4] Auckland North LiDAR 1m DEM (2016-2018) | LINZ Data Service
[5] Specified Auckland Areas Post Cyclone LiDAR Point Cloud | Auckland Council Open Data (arcgis.com)

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