Appendix E

Landslide Risk Assessment

Waitakere Coastal Communities

Appendix E – Muriwai Landslide Risk Assessment Report

Auckland Council

15 May 2024

→ **The Power of Commitment**

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E1. Introduction

E1.1 Purpose of this report

GHD has been engaged by Auckland Council (AC) to carry out landslide risk assessments as well as to provide 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 assessment is to present the results of a Quantitative Landslide Risk Assessment (QRA) carried out to estimate the risk of Loss of Life posed by large-scale[1] landslides to individuals in dwellings at Muriwai. We understand the outcome of the QRA will be used to inform future planning decisions, dwelling hazard designations and the revision of current building placards attached following Cyclone Gabrielle.

This report is an appendix to the overall GHD landslide risk report and should be read in conjunction with it, as well as associated appendices. The overall report contains additional background information and the results of other assessments carried out by GHD that are not included in this report. In particular, the GHD Muriwai Engineering Geological Report (hereafter referred to as the Appendix B report) provides a detailed description of the site as well as discussion of site geology and geomorphology, historical landsliding, landslide mapping, landslide classification and slope processes.

E1.2 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 entrained trees) occurred, some of which turned into saturated debris flows. These flows resulted in damage to buildings and infrastructure. Two fatalities occurred due to impact of landslides on private dwellings. In 1965 a storm also triggered landslides that destroyed dwellings and claimed two lives at Muriwai.

Following the event, rapid building assessment of residential properties was undertaken by Auckland Council 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). AC adjusted the location of placards following an area-wide Fahrböschung angle ('F-angle') assessment[2]. The current classifications are indicated by red or yellow dots in the attached figures.

The 'F-angle' assessment roughly estimates the maximum likely distance that a landslide will travel, taking into account the relative location of potentially at-risk properties to the source of risk, i.e. the hazardous slopes of the Muriwai Escarpment. Although the assessment criteria are relatively simplistic and conservative, the 'F-angle' provides a technical basis for classifying (placarding) properties quickly, which was appropriate for the rapid building assessments undertaken where decisions to evacuate people were required urgently.

E1.3 Scope

AC requested that this study be limited to the assessment of risks posed by 'large scale' landslide hazards originating from the main escarpment located to the south-east of Muriwai because the initial placard assessment was largely aimed at mitigating risks associated with these landslide hazards. Consequently, this report does not consider smaller, more localised landslide hazards that could originate (or may have already initiated) from other areas in Muriwai, such as within the footprint of individual dwellings, except for three specific properties attached to this report (Appendix E-2, E-3, E-4). Further clarification of this is given in Section 1.3 (footnote 3).

[1] In this report 'large scale' landslide hazards refer 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.
[2] Documented in an internal AC memo dated 9/03/2023, document ID: AKLCGEO-1790012875-1831

Smaller landslide hazards may include existing geohazards that have resulted from recent failures with the potential to pose risk to life in the immediate short-term (i.e. within the next few years) such as regression of translational failures that occur downslope of dwelling, failure of over-steepened fill and cut slopes, rockfall hazards associated with exposed rock faces/headscarps and/or loose debris remaining upslope of dwellings.

In addition, other possible geotechnical slope instability hazards relating to modified slopes (i.e. human made) may also exist and have potential to pose a risk to life - such as failures of fills, cuttings and damaged retaining walls. This represents hazards that may have a range of likelihood from *almost certain* to *possible*[3].

The QRA has been carried out in general accordance with the Australian Geomechanics Society Practice Note Guidelines for Landslide Risk Management, commonly known as AGS (2007c). A "risk to property" assessment was not part of our scope of work, which is specifically targeted on risk to life.

Dwellings that have been assessed to be in the path of landslide runout are considered as the elements at risk for this assessment. The risks posed to individuals in the 'open', such as people outside houses or situated on other public property such as roads, are not considered in this report.

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

This report has appended to it landslide risk assessment reports for three individual properties at 85 and 87 Domain Crescent and 207 Motutara Road, Muriwai (see Appendix E-2, E-3 and E-4, respectively).

This assessment considers geotechnical matters only. There may be other non-geotechnical considerations that affect the final property risk categorisation or placard designation of which GHD are not aware, such as flood risk or structural damage to property.

Although considered unlikely, GHD reserves the right to amend the opinions, conclusions and recommendations provided within this report, should additional geotechnical information become available.

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 1.1 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, 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 assumptions made by GHD described in this report. GHD disclaims liability arising from any of the assumptions being incorrect.

E1.4 Report structure

This report accompanies numerous other assessments associated with the Muriwai landslides. A list of companion reports is presented in Table E1. A3 plans referred to in this report are listed in Table E2 and additional images and data are presented in Appendices B-1, B-2 and B-3.

[3] The terminology used when referencing probabilities has been adopted from the Qualitative Measures of Likelihood table for assessing risk to property in AGS (2007c). For this assessment, these terms and associated probabilities are Certain = 0.99, Almost Certain = 0.1, Likely = 0.01, Possible = 0.001, Unlikely = 0.0001, Very Unlikely = >0.00001

Table E1 Summary of accompanying Muriwai reports

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

Table E2 List of maps and images in Appendix A that are associated with this report

Figure No.	Description
GENERAL SITE LAYOUT	
A101	OVERVIEW
ENGINEERING GEOLOGICAL PLANS	
A111	LEGEND
A112	OVERVIEW
A113 -A116	CLOSE-UP PLANS
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

E2. Landslide Risk Estimation

E2.1 Background

The 1998 Thredbo landslide (New South Wales, Australia), in which 18 persons were killed, highlighted the challenges faced from building upon steep slopes and led to the development of the Australian Geomechanics Society Landslide Risk Management (LRM) guidelines, published in 2007 and now commonly referred to as AGS (2007). This suite of guidelines is recognised nationally (Australia) and internationally as world-leading practice. The reader of this report is encouraged to consult the freely available LRM resources which can be accessed at: https://landsliderisk.org/.

Distilled down to its simplest form, AGS 2007c requires any landslide risk assessment to answer five questions as follows:

– What might happen? (Hazard Identification)
– How likely is it? (Likelihood or Frequency Analysis)
– What damage or injury might occur? (Consequence Analysis)
– How important is it? (Risk Estimation and Risk Evaluation)
– What can be done about it? (Risk Management).

The “Practice Note Guidelines for Landslide Risk Management” (AGS 2007c) provide technical guidance in relation to the processes and tasks to be undertaken by geotechnical practitioners who prepare LRM reports, including appropriate methods and techniques. The Practice Note is a statement of what constitutes good practice by a competent practitioner for LRM, including defensible and up to date methodologies, and provides guidance on the quality of assessment and reporting, including the outcomes to be achieved and how they are to be achieved.

The framework for landslide risk management is presented in Figure E1 and represents a framework widely used internationally.

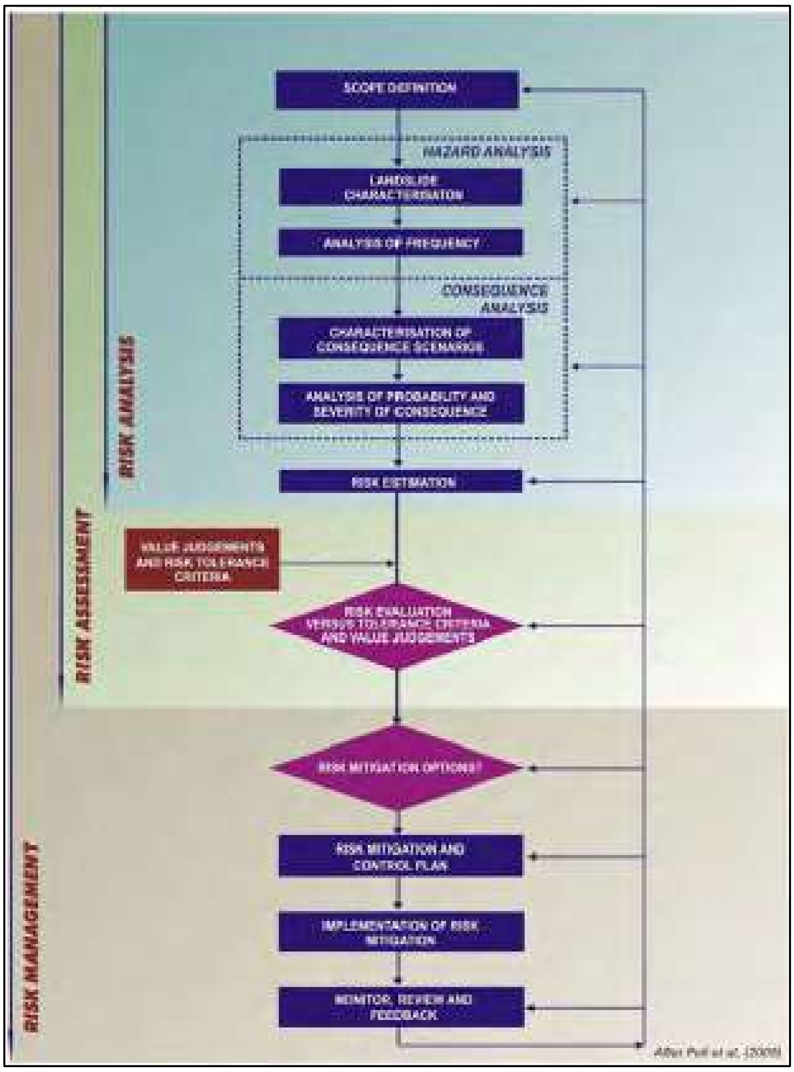

Figure E1 ***Framework for landslide risk management.***

E2.2 Risk assessment methodology

AGS (2007c) requires risks to loss of life to be estimated quantitatively for the person-most-at-risk. The person-most-at-risk will often but not always be the person with the greatest spatial temporal probability (i.e. the person most exposed to the risk). The Individual Risk-to-Life is defined as the risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide; or who follows a particular pattern of life that might subject him or her to the consequences of the landslide. The risk of 'loss-of-life' to an individual is calculated from:

$$\mathbf{R}_{(LoL)} = \mathbf{P}_{(H)} \times \mathbf{P}_{(S:H)} \times \mathbf{P}_{(T:S)} \times \mathbf{V}_{(D:T)}$$

Where:

$\mathbf{R}_{(LoL)}$	is the risk (annual probability of loss of life (death) of an individual).
$\mathbf{P}_{(H)}$	is the annual probability of the landslide.
$\mathbf{P}_{(S:H)}$	is the probability of spatial impact of the landslide impacting a building (location) taking into account the travel distance and travel direction given the event.
$\mathbf{P}_{(T:S)}$	is the temporal spatial probability (e.g. of the building or location being occupied by the individual) given the spatial impact and allowing for the possibility of evacuation given there is warning of the landslide occurrence.
$\mathbf{V}_{(D:T)}$	is the vulnerability of the individual (probability of loss of life of the individual given the impact).

The main objectives of risk evaluation are usually to compare the assessed risk to risk levels that are acceptable or tolerable to the community, and therefore to decide whether to accept, tolerate or treat the risks, and to set priorities for remediation. The Tolerable Risk Criteria are usually imposed by the regulator, unless agreed otherwise with the owner/client. AGS (2007d) provides discussion and gives the AGS recommendations in relation to tolerable risk for loss of life. These are discussed in Section E2.3.

E2.3 Risk Evaluation

The main objectives of risk evaluation are usually to compare the assessed risk to risk levels that are acceptable or tolerable to the community, and therefore to decide whether to accept, tolerate or treat the risks and to set priorities for remediation. The Tolerable Risk Criteria are usually imposed by the regulator, unless agreed otherwise with the owner/client. AGS (2007d) provides discussion and gives the AGS recommendations in relation to tolerable risk for loss of life. These are summarized in the table below.

Table E3 AGS Suggested Tolerable loss of life individual risk

Situation	Suggested Tolerable Loss of Life Risk for the person most at risk
Existing Slope / Existing Development	10^{-4} per annum (1E-4 pa), or 1 in 10,000 pa
New Constructed Slope / New Development / Existing Landslide	10^{-5} per annum (1E-5 pa), or 1 in 100,000 pa

It is important to distinguish between “acceptable risks” and “tolerable risks”. AGS (2007c) states that:

Tolerable risks are risks within a range that society can live with so as to secure certain benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if practicable.

Acceptable risks are risks which everyone affected is prepared to accept. Acceptable risks are usually considered to be one order of magnitude lower than the Tolerable risks.

Appended to this report are GHD landslide risk assessment reports for three individual properties at 85 and 87 Domain Crescent and 207 Motutara Road, that were carried out at the request of AC (see Appendix E-2, E-3, and E-4, respectively). These differ from this area-wide risk study as they pertain to the hazard from localised slope instability within the property boundary. The methodology for these is explained in full in the report for each site and further details are not discussed in this report (the summary of risk for these sites is reproduced in Section E3.2 of this report).

E2.4 Landslide Risk Assessment Uncertainty

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. By its very nature much of the data, including historical and current inventories, may be incomplete while understanding of the triggering events has a degree of uncertainty attached to it. Judgement is required to estimate the nature and size of potential hazards, their frequency of occurrence and their impact on a variety of elements at risk. As these judgements are based on the knowledge, experience and understanding of the assessor, it is not unusual for different assessors to make different judgements about the level of risk.

The thought process used in establishing likelihoods, consequences and determining spatial and temporal factors for properties at Muriwai has been documented for transparency. It is important to recognise the inherent imprecisions associated with the risk assessment process given the limitations of the inputs outlined above. Generally, the levels of likelihoods and risks should be thought of as being within a range of typically +/- half an order of magnitude at best.

While the basis for the judgements contained in this report are well documented, and the levels of risk considered to be good representations of reality, the accuracy and precision of the process should not be overestimated and should always be used in an appropriate manner in combination with risk management including mitigation and treatment options.

E2.5 Hazard Characterisation

E2.5.1 Landslide Hazards

AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This is generally a predictive exercise based on knowledge and understanding of the geological and geomorphological setting with a view to assembling historical evidence for past hazard events.

As noted above, the risk assessment presented in this report is limited to the assessment of risks posed by 'large scale' landslide hazards originating from the main escarpment located to the south-east of Muriwai. Smaller, more localised landslide hazards that could originate (or may have already initiated) from other areas in Muriwai such as small slips within the footprint of individual properties are not considered in this report, unless they have caused widespread damage.

The Appendix B report provides a detailed description of the landslide hazards at the site. The following summary provides an overview of the February 2023 landslides for context in this report.

Based on the GHD mapping and observations, the majority of the landslides[4] originating from the main escarpment comprised an initial translational failure. These failures were typically quite shallow, often in the order of 0.5 m to 1 m deep. Following initial failure, many of the landslide masses developed into rapid debris flows travelling various distances downslope, with some debris crossing Domain Crescent and Motutara Road.

In the southern part of the escarpment (i.e. Geomorphological Zone 3 as defined in the Appendix B report) the debris flows are typically more channelised flows, being somewhat confined by topographic features such as gullies. While this also occurs in the northern parts of the escarpment (i.e. Geomorphological Zone 2), these features are less prevalent in that zone, and the debris flows are commonly broader.

The width of the mapped landslide main (head) scarps / landslide crowns ranges from about 10 m to in excess of 50 m across the main escarpment. The width of the zone of deposited debris at the toe of each landslide varies depending on the extent of channelisation, with some landslide debris spreading out and increasing while in other areas the debris becomes more confined and narrows. The mapped landslides have estimated volumes ranging in the order from tens to thousands of cubic metres.

The landslide hazards considered as part of this assessment are as follows:

- **LS1a** (Landslide Hazard 1a): Landslides originating from the upper sections of the main escarpment that subsequently form debris flows that travel towards houses / dwellings located on or at the toe of the escarpment. This hazard is representative of the extensive landsliding that occurred across the escarpment in February 2023. This hazard affects areas of the site in the 'predicted modelled debris runout zone' as defined in Section 2.5.2.1.
- **LS1b** (Landslide Hazard 1b): Hazard as described in LS1a above however a more conservative (i.e. longer) modelled landslide runout zone has been adopted (See Section 2.5.2.1 below).
- **LS2a** (Landslide Hazard 2a): Landslides originating from the upper sections of the main escarpment that subsequently form debris flows that travel towards houses / dwellings located on or at the toe of the escarpment that are more frequent but less damaging than LS1a. This hazard is analogous to the more localised landsliding that occurred during the 1965 landslide event.
- **LS2b** (Landslide Hazard 2b): Hazard as described in LS2a above however a more conservative (i.e. longer) modelled landslide runout zone has been adopted (See Section 2.5.2.1 below).

E2.5.2 Landslide runout

The landslide runout was assessed using numerical modelling methods discussed below. The dwellings that have been assessed to be in the path of landslide runout are considered as the elements at risk for this assessment. The risks posed to individuals in the 'open', such as people outside houses or situated on other public property such as roads, are not considered in this report.

[4] Landslide terminology used in this report generally follows the scheme proposed by Cruden & Varnes (1996).

2.5.2.1 RAMMS debris flow modelling

The ‘RAMMS:Debrisflow module’ (RAMMS) was used to assess landslide runout and the spatial extent of areas potentially affected by landsliding. RAMMS is a numerical software package developed by the WSL Institute for Snow and Avalanche Research and is used to simulate the runout of debris-laden flows in complex terrain. The modelled landslide runout zones are referred to in this report as the ‘Predicted modelled debris runout zone’. This assessment is discussed in the Muriwai RAMMS debris flow analysis report in Appendix D.

The risk assessment presented in this report has relied on the outputs of the RAMMS modelling as the basis for determining areas of the site that could be affected by landsliding. The predicted modelled debris runout zones are presented in Figures A206 to A209 in Appendix A.

2.5.2.2 Empirical landslide runout assessment

Empirical methods have been used to further compare the landslide runout distances predicted using RAMMS and the observed landslide runouts. The empirical methods typically predicted a similar landslide runout to the observed landslide runouts This assessment is discussed in the Appendix B report.

E2.6 Likelihood of landsliding ($P_{(H)}$)

E2.6.1 Rainfall and relationship to landsliding

Council provided GHD with an assessment of available rainfall data associated with Cyclone Gabrielle (Auckland Council 2023) (AC memo). During Cyclone Gabrielle, the tipping bucket rain gauge at Muriwai failed and was inundated by flood waters. The AC memo also provided rainfall analysis using AC’s Quantitative Precipitation Estimate (QPE) Rain Radar System, which is a real-time rainfall product that utilises the MetService radar. The rainfall data presented by AC indicates a peak rainfall total for Muriwai during the event of 146.9 mm, occurring over 12-hour period. This total is more than the 100-year event at a 12-hour duration. The data suggests that for the 12-hour duration rainfall, the Annual Recurrence Interval (ARI) is more than 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 as a result of the relatively short statistical rainfall records available in New Zealand. For the other durations modelled, the rainfall was below the 100-year event.

The AC memo recommended that an envelope of “risk” is estimated as the ARI figures will change over time as these events are incorporated into the statistical record. The AC memo states that, in general, it is considered reasonable to consider the Cyclone Gabrielle event to be in the range of 100 to 250 year ARI. For this assessment we have assumed that the annual likelihood of a landslide event occurring that is similar in magnitude to the February 2023 event, is about 1 in 100 (i.e., 0.01). This is considered to have a *likely* probability of occurrence as per AGS (2007c) Appendix C criteria.

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 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 August 27, 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 3-day rainfall event of similar magnitude is less than 100. Considering the 1965 landslide event affected a considerably smaller area of the Muriwai escarpment than the recent 2023 event, suggests that the triggering rainfall event was smaller. Given the uncertainties above, we have assumed that a rainfall event with an ARI of about 50, could trigger a similar landslide event to that experienced in 1965.

The AC memo further recommended that risk assessment reports consider the potential for climate change to increase the frequency of high intensity rainfall. We understand that the National Institute of Water and

Atmospheric Research (NIWA) has projected a 20% increase in rainfall intensity over the next 100 years which suggests that a 250-year ARI event could increase to a 50-year ARI event. Consequently, we have also included sensitivity checks using more frequent ARI values as discussed in Section E2.6.2.

E2.6.2 Partitioning of likelihood

The rainfall events discussed in Section E2.6.1, the estimation of recurrence intervals for those events and the occurrence of the observed hazards, form the basis for the estimated probability of occurrence for the landslide hazards. However, observations of the recent and past events noted that not all similar slopes failed as a result of the initiating storm event and as such, additional considerations for probability of occurrence have been included within the analysis by using conditional probabilities as follows:

$$P_{(H)} = P_{(H'1)} \times P_{(H'2)}$$

Where:

> $P_{(H'1)}$ = Probability that the rainfall threshold for the landslide hazard is exceeded, which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or 0.01 for LS1a and LS1b (see Section E2.6.1) or 1 in 50 or 0.02 under the influence of future climate change. For LS2a and LS2b, $P_{(H'1)}$ is assumed to be 1 in 50 or 0.02. Under the influence of future climate change we have assumed the ARI for the same event will be twice as likely (i.e. an ARI 100 event becomes an ARI 50 event).

> $P_{(H'2)}$ = Probability that the slope for the specific assessment fails, which we relate to the proportion of the area of actual failed slopes out of the total area of all slopes present. This probability is based on a spatial analysis of the total area of failed landslides slopes compared to the total area of all slopes in each of the geomorphological zones defined in the Appendix B report. The adopted $P_{(H'2)}$ values for LS1a and LS1b are presented in Table E4.

Geomorphological Zones 1 and 6 have both been assigned likelihood values that differ from those of other geomorphological zones. As discussed in the Appendix B report, no landslides were triggered in Zone 1 and only relatively localised small-scale landslides with limited runout were triggered in Zone 6. However, historical landslide headscarp features are apparent in the LiDAR data across these areas and we interpret this to mean that these areas are susceptible to large, potentially damaging landslides, especially in future storm events that are larger than Cyclone Gabrielle. On this basis, we consider a $P_{(H'2)}$ value that is greater than zero for the $P_{(H'1)}$ 0.01 (i.e. 1 in 100-year storm) event. Given there were either no or very limited landslides observed in these zones in February 2023, we have adopted a $P_{(H'2)}$ value of 0.01. There is no basis for estimating the potential for landslides during less frequent, more intense storms, i.e. a 1 in 1000-year storm ($P_{(H'1)}$ of 0.001).

For Zones 2, 3 and 4 the adopted $P_{(H'2)}$ value for LS2a / LS21b is 0.02 based on spatial analysis of historical mapping of the 1965 landslide area.

Table E4 Summary of adopted $P_{(H'2)}$ factors for LS1a and LS1b

Geomorphological zone	$P_{(H'2)}$
1	0.01
2	0.29
3	0.07
4	0.56
5	0.06
6	0.01

E2.7 Probability of spatial impact ($P_{(S:H)}$)

E2.7.1 Landslide upslope of dwelling

The AGS definition of spatial probability is represented by single term $P_{(S:H)}$ and is described as the probability of spatial impact by the landslide on the element at risk, given the landslide occurs and taking into account the travel direction and travel distance or reach.

For areas of the site located within the predicted modelled debris runout zones (LS1a, LS2a), $P_{(S:H)}$ = 1.

For areas of the site located within the conservative modelled debris runout zones (LS1b, LS2b), we have assumed that $P_{(S:H)}$ is about one order of magnitude lower (i.e. about a 10% probability of exceeding the predicted modelled debris runout zones). $P_{(S:H)}$ is therefore = 0.1.

E2.7.2 Landslide below dwelling

Landslides below dwellings are not considered in this study as all landslides occurred on the escarpment, upslope of the dwellings, which are located at the toe of the slope. Dwellings at the top of the escarpment (i.e. on the west side of Oaia Road) that could be undermined by the regression of the escarpment edge in future landslide events are reported in a separate, future study.

E2.8 Temporal probability ($P_{(T:S)}$)

This assessment has not considered specific occupancy scenarios for each individual dwelling. We acknowledge that the occupancy of each dwelling could vary significantly depending on the demographics of the residents and the usage of the dwelling. For example, some may be predominantly used as holiday accommodation, occupied mainly on weekends, whereas others could be permanently occupied by working families. For risk assessments conducted at this scale, and given potential future planning decisions, it is typically not appropriate to consider unique occupancy scenarios because the usage of each dwelling will likely change each time the ownership of the property changes.

We have not considered the possibility that individuals could evacuate before the landslide event occurs as the landslide history at Muriwai suggests landslides occur rapidly with few obvious signs of failure prior to the event occurring. It is also not reasonable to expect individuals to be aware of potential landsliding should the rainfall triggering event occur during the night.

This assessment has assumed the following occupancies:

– Dwellings are typically occupied for 15 hours each day during weekdays;
– On weekends, dwellings are occupied for about 20 hours each day;

The percentage of time a dwelling is occupied is therefore about 68%.

Any further delineations of the spatial variations in occupancy (i.e. if a bedroom is at the front or the rear of the house etc) are not considered feasible or warranted within the context of the precision of this assessment.

E2.9 Vulnerability ($V_{(D:T)}$)

AGS (2007c, Appendix F) includes a table of vulnerability values for various inundation and building damage scenarios as adapted by Finlay et al (1999). It is important to note that the AGS (2007c) vulnerability table does not adequately cater for all the building damage scenarios GHD has observed in the Waitakere area. GHD has therefore further adapted this table and combined it with information from the TfNSW Guide to Slope Risk Analysis (2014) as well as observations of damage to buildings and structures resulting from the recent landslides in the Waitakere area (Table E5).

These values have been used as a guide and expert judgement has been applied to select a value within the range of values where appropriate.

Table E5 Summary of vulnerability values adopted for the Waitakere area

Case	Range	Typical value used in assessments	Comments
Person in a building that collapses under impact from debris flow	0.8 -1.0	0.9	Death is almost certain. Evacuation unlikely to occur
If building is inundated with debris and the person is buried	0.8 -1.0	0.8	Very high potential for death Evacuation unlikely to occur
If building is inundated with debris but no collapse occurs and the person is not buried	0.01 -0.1	0.1	High chance of survival Evacuation unlikely to occur
If the debris strikes the building only	0.001-0.05	0.01	High chance of survival

Most dwellings constructed below the escarpment at Muriwai comprise timber frame structures with various forms of lightweight cladding such as weatherboard and fibre cement. The extent of damage to dwellings varied considerably depending on where each was located with respect to the path of each landslide. During the mapping and reconnaissance visits undertaken by GHD it was commonly observed that total destruction occurred to the structure when the flow height of the landslide exceeded approximately 0.5 m. Figure E2 presents an example of a dwelling that was completely destroyed, sadly resulting in two fatalities. It is important to note that total destruction also occurred to many other dwellings in Muriwai that had already been evacuated. Had evacuation not occurred the survivability in many of these properties would have been very low.

As discussed in the Appendix B report, the 1965 Muriwai landslides destroyed two dwellings, killing two of four people who were occupying one of the houses. One house was completely destroyed by the landslide and collapsed while the other was “swept off its foundation” and carried across Domain Crescent where it came to rest surrounded by debris (Hayward 2022).

In many observed instances trees entrained in the landslide mass played a large role in the destruction of dwellings in the 2023 event (Figure E4 to Figure E7). Accumulations of trees and other vegetation were commonly rafted and entrained towards the top of each slide mass which subsequently impacted the upslope side of dwellings. The thickness of these accumulated piles of vegetation debris sometimes exceeded 3 m. It is clear that the direct impact effects of the vegetation piles into dwellings were responsible for extensive damage and complete destruction in a number of circumstances.

Figure E2 Example of a dwelling completely destroyed on Motutara Road where two fatalities occurred.

Figure E3 View of same dwelling pictured in Figure E2 showing overall view of landslide with accumulated vegetation at toe of slide.

Figure E4 *Example of a dwelling on Domain Crescent completely destroyed by landslide with large pile of accumulated vegetation debris on upslope side.*

Figure E5 *View of upslope side of completely destroyed timber frame dwelling. Note large pile of accumulated vegetation debris on left.*

Figure E6 *View of the same dwelling pictured in Figure E5 taken further upslope. Note mixture of soil debris and vegetation. Residence has been moved several metres downslope.*

Figure E7 *View of remains of completely destroyed house on slope above Motutara Road. Note mixture of soil debris and vegetation.*

The observations of building damage at Muriwai are in good agreement with a study by Kang et al. (2016) that compared physical vulnerability of different types of building structures to debris flow events. In this context, physical vulnerability is a representation of the expected degree of loss and is quantified on a scale of 0 (no damage) to 1 (total destruction) (Fell et al. 2005). This should not be confused with the vulnerability to individuals (probability of loss of life of the individual given the impact). Kang et al. (2016) developed a number of vulnerability curves using the degree of damage to buildings coupled with intensities of the debris flow events (Figure E8).

The Kang et al. (2016) vulnerability curves for both flow depth and velocity typically are in good agreement with the Muriwai observations and modelling. For example, total destruction of a timber frame structure becomes increasingly likely as the flow depth approaches 1 m thickness.

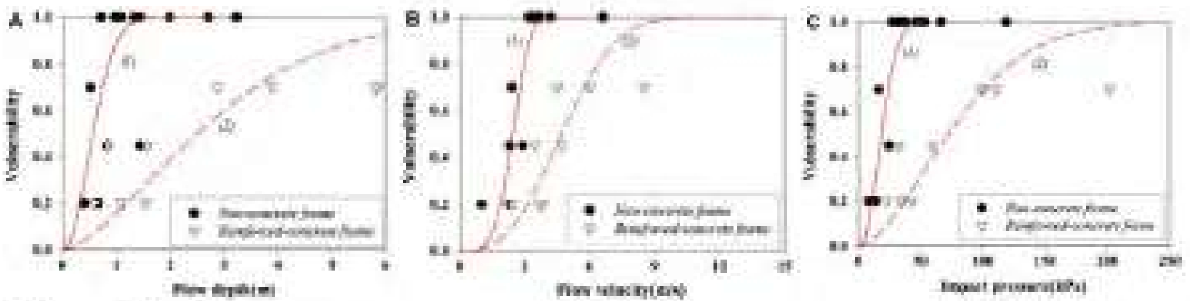

Figure E8 ***Debris flow vulnerability (physical vulnerability) curves as a function of the flow depth, flow velocity, and impact pressure (Kang 2016).***

Despite the total destruction of many houses in Muriwai, a number of houses were impacted by more than 0.5 m thickness of debris and associated vegetation and were not completely destroyed. For example, Figure E9 to Figure E11 shows a two-storey dwelling on Domain Crescent that toppled over, leaving the upper storey largely intact. The ground floor of the structure has completely collapsed and is inundated with debris. In this example, had individuals been present on the ground floor it is unlikely they would have survived. However, the survivability on the upper floor is assessed to be relatively high, perhaps only leading to injuries should individuals have been present. This example demonstrates the challenges of adopting a representative vulnerability value for individuals occupying a single dwelling.

Figure E12 and Figure E13 present another example of a two-storey timber frame house impacted by a landslide. The dwelling has deformed as is evident by the tilting of walls and distortion of door frames, but the structure is largely intact, and no inundation appears to have occurred. The survivability from this damage is also considered to be very high.

There are many factors that could have contributed to some houses experiencing significantly less damage than others, despite the reasons not being immediately obvious based on observations alone. For example, the flow velocity in some instances may have been very low by the time the distal end of the flow reached a house. Alternatively, the construction methods of some houses may be more resistant to landslide impacts than others. Given these uncertainties it is not reasonable or practical to assign unique vulnerability values to different dwellings at the site.

Figure E9 *Example of a dwelling on Domain Crescent where ground floor of the structure has collapsed causing house to topple over with the upper storey remaining largely intact.*

Figure E10 *View of side profile of dwelling pictured in Figure E9, showing collapse of the ground floor and build-up of vegetation debris at rear.*

Figure E11 Aerial view of dwelling pictured in Figure E10. The debris flow originated at the far right of the photo.

Figure E12 Side view of home above Motutara Road. Note tilting of upper storey wall and deformed window frame.

Figure E13 View of upslope side of dwelling pictured in Figure E12 showing accumulated landslide debris against rear wall.

Table E6 presents a summary of the adopted vulnerability probability factors used in this assessment.

Table E6 Summary of adopted vulnerability probability factors

Hazard	Vulnerability ($V_{(D:T)}$)	Comments
LS1a	0.8	Building is likely to be inundated and may collapse. Very high potential for death. Evacuation unlikely to occur. Since 1965, four fatalities have occurred at Muriwai where building collapse has occurred.
LS1b	0.8	Building is likely to be inundated and may collapse. Very high potential for death. Evacuation unlikely to occur. Since 1965, four fatalities have occurred at Muriwai where building collapse has occurred.
LS2a	0.8	Building is likely to be inundated and may collapse. Very high potential for death. Evacuation unlikely to occur. Since 1965, four fatalities have occurred at Muriwai where building collapse has occurred.
LS2b	0.8	Building is likely to be inundated and may collapse. Very high potential for death. Evacuation unlikely to occur. Since 1965, four fatalities have occurred at Muriwai where building collapse has occurred.

E2.10 Risk estimation

A summary of the risk estimation for each Geomorphological Zone is presented in Table E7 below. A sensitivity check assuming a higher probability of occurrence for $P_{(H)}$ is included for comparative purposes. As can be seen, this increases the risk and, in some cases in Zones 1 and 6, changes the risk evaluation.

Table E7 ***Summary of risk estimation for each hazard type by Geomorphological Zone***

Geomorphological Zone	Hazard	Description	Annual probability of the landslide $P_{(H)}$		Spatial probability	Temporal probability	Vulnerability	Risk	Risk Evaluation*
			$P_{(H'1)}$	$P_{(H'2)}$	$P_{(S:H)}$	$P_{(T:S)}$	$V_{(D:T)}$	$R_{(LOL)}$	
1	LS1a	Debris Flow upslope of dwelling	0.010	0.01	1.00	0.68	0.80	5.4×10^{-5}	Tolerable
	LS1a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*1.00*	*0.68*	*0.80*	*1.1×10^{-4}*	*Not tolerable*
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	0.010	0.01	0.10	0.68	0.80	5.4×10^{-6}	Acceptable
	LS1b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*0.10*	*0.68*	*0.80*	*1.1×10^{-5}*	*Tolerable*
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	0.010	0.01	1.00	0.68	0.80	5.4×10^{-5}	Tolerable
	LS2a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*1.00*	*0.68*	*0.80*	*1.1×10^{-4}*	*Not tolerable*
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	0.010	0.01	0.10	0.68	0.80	5.4×10^{-6}	Acceptable
	LS2b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*0.10*	*0.68*	*0.80*	*1.1×10^{-5}*	*Tolerable*
2	LS1a	Debris Flow upslope of dwelling	0.010	0.29	1.00	0.68	0.80	1.6×10^{-3}	Not tolerable
	LS1a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.29*	*1.00*	*0.68*	*0.80*	*3.2×10^{-3}*	*Not tolerable*
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	0.010	0.29	0.10	0.68	0.80	1.6×10^{-4}	Not tolerable
	LS1b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.29*	*0.10*	*0.68*	*0.80*	*3.2×10^{-4}*	*Not tolerable*
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	0.020	0.02	1.00	0.68	0.80	2.2×10^{-4}	Not tolerable
	LS2a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*1.00*	*0.68*	*0.80*	*4.4×10^{-4}*	*Not tolerable*
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	0.020	0.02	0.10	0.68	0.80	2.2×10^{-5}	Tolerable
	LS2b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*0.10*	*0.68*	*0.80*	*4.4×10^{-5}*	*Tolerable*
3	LS1a	Debris Flow upslope of dwelling	0.010	0.07	1.00	0.68	0.80	3.8×10^{-4}	Not tolerable
	LS1a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.07*	*1.00*	*0.68*	*0.80*	*7.6×10^{-4}*	*Not tolerable*
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	0.010	0.07	0.10	0.68	0.80	3.8×10^{-5}	Tolerable
	LS1b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.07*	*0.10*	*0.68*	*0.80*	*7.6×10^{-5}*	*Tolerable*
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	0.020	0.02	1.00	0.68	0.80	2.2×10^{-4}	Not tolerable
	LS2a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*1.00*	*0.68*	*0.80*	*4.4×10^{-4}*	*Not tolerable*
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	0.020	0.02	0.10	0.68	0.80	2.2×10^{-5}	Tolerable

Geomorphological Zone	Hazard	Description	Annual probability of the landslide $P_{(H)}$		Spatial probability	Temporal probability	Vulnerability	Risk	Risk Evaluation*
			$P_{(H'1)}$	$P_{(H'2)}$	$P_{(S:H)}$	$P_{(T:S)}$	$V_{(D:T)}$	$R_{(LOL)}$	
	LS2b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*0.10*	*0.68*	*0.80*	*4.4×10^{-5}*	*Tolerable*
4	LS1a	Debris Flow upslope of dwelling	0.010	0.56	1.00	0.68	0.80	3.0×10^{-3}	Not tolerable
	LS1a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.56*	*1.00*	*0.68*	*0.80*	*6.1×10^{-3}*	*Not tolerable*
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	0.010	0.56	0.10	0.68	0.80	3.0×10^{-4}	Not tolerable
	LS1b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.56*	*0.10*	*0.68*	*0.80*	*6.1×10^{-4}*	*Not tolerable*
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	0.020	0.02	1.00	0.68	0.80	2.2×10^{-4}	Not tolerable
	LS2a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*1.00*	*0.68*	*0.80*	*4.4×10^{-4}*	*Not tolerable*
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	0.020	0.02	0.10	0.68	0.80	2.2×10^{-5}	Tolerable
	LS2b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*0.10*	*0.68*	*0.80*	*4.4×10^{-5}*	*Tolerable*
5	LS1a	Debris Flow upslope of dwelling	0.010	0.06	1.00	0.68	0.80	3.3×10^{-4}	Not tolerable
	LS1a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.06*	*1.00*	*0.68*	*0.80*	*6.5×10^{-4}*	*Not tolerable*
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	0.010	0.06	0.10	0.68	0.80	3.3×10^{-5}	Tolerable
	LS1b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.06*	*0.10*	*0.68*	*0.80*	*6.5×10^{-5}*	*Tolerable*
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	0.020	0.02	1.00	0.68	0.80	2.2×10^{-4}	Not tolerable
	LS2a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*1.00*	*0.68*	*0.80*	*4.4×10^{-4}*	*Not tolerable*
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	0.020	0.02	0.10	0.68	0.80	2.2×10^{-5}	Tolerable
	LS2b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.040*	*0.02*	*0.10*	*0.68*	*0.80*	*4.4×10^{-5}*	*Tolerable*
6	LS1a	Debris Flow upslope of dwelling	0.010	0.01	1.00	0.68	0.80	5.4×10^{-5}	Tolerable
	LS1a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*1.00*	*0.68*	*0.80*	*1.1×10^{-4}*	*Not tolerable*
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	0.010	0.01	0.10	0.68	0.80	5.4×10^{-6}	Acceptable
	LS1b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*0.10*	*0.68*	*0.80*	*1.1×10^{-5}*	*Tolerable*
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	0.010	0.01	1.00	0.68	0.80	5.4×10^{-5}	Tolerable
	LS2a	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*1.00*	*0.68*	*0.80*	*1.1×10^{-4}*	*Not tolerable*
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	0.010	0.01	0.10	0.68	0.80	5.4×10^{-6}	Acceptable

Geomorphological Zone	Hazard	Description	Annual probability of the landslide $P_{(H)}$		Spatial probability	Temporal probability	Vulnerability	Risk	Risk Evaluation*
			$P_{(H'1)}$	$P_{(H'2)}$	$P_{(S:H)}$	$P_{(T:S)}$	$V_{(D:T)}$	$R_{(LOL)}$	
	LS2b	*Sensitivity Check (Debris Flow upslope of dwelling)*	*0.020*	*0.01*	*0.10*	*0.68*	*0.80*	*1.1×10^{-5}*	*Tolerable*

**The evaluation is a guide only based on recommendations from AGS (2007) which provides a suggested tolerable annual Loss of Life Risk for the person most at risk (existing slopes) is 1×10^{-4} (1 in 10,000).*

E3. Conclusions

The travel paths for the assessed landslide hazards are based on the 'predicted modelled debris runout zone' as discussed in Section E2.5 (see Figures A206 to A209 in Appendix A). The estimated risks presented in this report for debris flow hazards only apply to areas of the site located within these zones. A summary of the estimated risks is presented below.

We emphasise that this evaluation is a guide only based on recommendations from AGS (2007) which provides a suggested tolerable Loss of Life Risk for the person most at risk (existing slopes).

E3.1 Loss of life risk from debris flow

E3.1.1 Geomorphological Zone 1

With regards to the LS1a hazard, these risks have been assessed to be tolerable according to the evaluation against the AGS (2007c) suggested tolerable Loss of Life Risk limit for the person most at risk. The risk associated with LS2a has also been estimated to be below the AGS (2007c) suggested tolerable Loss of Life Risk limit. Using a higher likelihood related to climate change for each of these cases would result in higher levels of risk evaluated as not tolerable against the AGS (2007c) recommended criteria (see Table E3).

Table E8 Summary of risk estimation, Zone 1

Geomorphological Zone	Hazard	Description	Risk Evaluation
1	LS1a	Debris Flow upslope of dwelling	Tolerable
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	Acceptable
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	Tolerable
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	Tolerable

E3.1.2 Geomorphological Zone 2

With regards to hazards LS1a, LS1b and LS2a, we have estimated these risks to **exceed** the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (Table E9). Using a higher likelihood related to climate change for each of these cases also results in higher levels of risk evaluated as not tolerable against the AGS (2007c) recommended criteria (see Table E3).

Table E9 Summary of risk estimation, Zone 2

Geomorphological Zone	Hazard	Description	Risk Evaluation
2	LS1a	Debris Flow upslope of dwelling	Not tolerable
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	Not tolerable
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	Not tolerable
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	Tolerable

E3.1.3 Geomorphological Zone 3

With regards to hazards LS1a and LS2a, we have estimated these risks to **exceed** the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (Table E10). Using a higher likelihood related to climate change for each of these cases also results in higher levels of risk evaluated as not tolerable against the AGS (2007c) recommended criteria (see Table E3).

Table E10 Summary of risk estimation, Zone 3

Geomorphological Zone	Hazard	Description	Risk Evaluation
3	LS1a	Debris Flow upslope of dwelling	Not tolerable
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	Tolerable
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	Not tolerable
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	Tolerable

E3.1.4 Geomorphological Zone 4

With regards to hazards LS1a, LS1b and LS2a, we have estimated these risks to **exceed** the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (Table E11). Using a higher likelihood related to climate change for each of these cases also results in higher levels of risk evaluated as not tolerable against the AGS (2007c) recommended criteria (see Table E3).

Table E11 Summary of risk estimation, Zone 4

Geomorphological Zone	Hazard	Description	Risk Evaluation*
4	LS1a	Debris Flow upslope of dwelling	Not tolerable
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	Not tolerable
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	Not tolerable
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	Tolerable

E3.1.5 Geomorphological Zone 5

With regards to hazards LS1a and LS2a, we have estimated these risks to **exceed** the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (Table E12). Using a higher likelihood related to climate change for each of these cases also results in higher levels of risk evaluated as not tolerable against the AGS (2007c) recommended criteria (see Table E3).

Table E12 Summary of risk estimation, Zone 5

Geomorphological Zone	Hazard	Description	Risk Evaluation
5	LS1a	Debris Flow upslope of dwelling	Not tolerable
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	Tolerable
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	Not tolerable
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	Tolerable

E3.1.6 Geomorphological Zone 6

With regards to the LS1a hazard, these risks have been assessed to be tolerable according to the evaluation against the AGS (2007c) suggested tolerable Loss of Life Risk limit for the person most at risk as presented in Table E13. The risk associated with LS2a has also been estimated to be below the AGS (2007c) suggested tolerable Loss of Life Risk limit. Using a higher likelihood related to climate change for each of these cases would result in higher levels of risk evaluated as not tolerable against the AGS (2007c) recommended criteria (see Table E3).

Table E13 Summary of risk estimation, Zone 6

Geomorphological Zone	Hazard	Description	Risk Evaluation
6	LS1a	Debris Flow upslope of dwelling	Tolerable
	LS1b	Debris Flow upslope of dwelling (longer modelled runout)	Acceptable
	LS2a	Debris Flow upslope of dwelling (more frequent, less widespread)	Tolerable
	LS2b	Debris Flow upslope of dwelling (more frequent, less widespread with longer modelled runout)	Tolerable

E3.2 Loss of life risk for 85 and 87 Domain Crescent and 207 Motutara Road

The unmitigated risk for 85 and 87 Domain Crescent in Zone 3 and 207 Motutara Road in Zone 2 is summarised in Table E14 (see Appendix E-2, E-3 and E-4 respectively).

Table E14 Summary of unmitigated risk estimation for 85 and 87 Domain Crescent and 207 Motutara Road, Muriwai

Hazard	Description	Risk Evaluation
LS1 – 85 Domain Crescent	Landslide upslope of dwelling	Not tolerable
LS1 – 87 Domain Crescent	Landslide upslope of dwelling	Not tolerable
LS1 – 207 Motutara Road	Landslide upslope of dwelling	Tolerable
LS2 – 207 Motutara Road	Regression of existing landslide	Not tolerable

E3.3 Closure

This report has presented the results of a quantitative risk assessment to estimate the risk of Loss of Life posed by large-scale landslides to individuals in dwellings at Muriwai. This assessment has only considered the 'large scale' landslide hazards originating from the main escarpment located to the south-east of Muriwai. This assessment has not considered risks to dwellings at the crest of the escarpment (i.e. along Oaia Road) that are susceptible to undermining due to regression of the escarpment.

We understand Council are currently reviewing their tolerable and acceptable risk criteria for risks associated with landsliding. We recommend Council review the risk assessment presented in this report against the Council's own risk criteria to inform decisions on future land planning, dwelling hazard designations and the revision of current building placards.

As discussed above, this report considers geotechnical matters only. There may be other non-geotechnical considerations that affect final placard designation of which GHD are not aware, such as flood risk and structural damage to property.

E4. References

AGS (2000). Landslide risk management concepts and guidelines. Australian Geomechanics Society. Australian Geomechanics Vol 35, No 1, 49-92

AGS (2002). Landslide risk management concepts and guidelines. Australian Geomechanics Society. Australian Geomechanics Vol 37, No 2, 1-44

AGS (2007a). Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Management. Australian Geomechanics Society, Australian Geomechanics, Vol 42, No1.

AGS (2007b). Commentary on Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Management, Australian Geomechanics Society, Australian Geomechanics, Vol 42, No1.

AGS (2007c). Practice Note Guidelines for Landslide Risk Management Australian Geomechanics Society. Australian Geomechanics, Vol 42, No1.

AGS (2007d). Commentary on Practice Note Guidelines for Landslide Risk Management. . Australian Geomechanics, Vol 42, No1.

Cruden D.M. & Varnes D. J. (1996). Landslide types and processes. In: Turner A.K.; Schuster R.L. (eds) Landslides: Investigation and Mitigation. Transportation Research Board, U.S. National Academy of Sciences, Special Report, 247: 36-75.

P J Finlay, G R Mostyn & R Fell (1999). 'Landslides: Prediction of Travel Distance and Guidelines for Vulnerability of Persons'. Proc 8th. Australia New Zealand Conference on Geomechanics, Hobart. Australian Geomechanics Society, ISBN 1 86445 0029, Vol 1, pp.105-113.

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

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.

Kang, Hs., Kim, Yt. (2016) The physical vulnerability of different types of building structure to debris flow events. Nat Hazards 80, 1475–1493. https://doi.org/10.1007/s11069-015-2032-z

New South Wales Government, Transport for New South Wales 'Guide to Slope Risk Analysis' Version 4, April 2014.

E5. 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, 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 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.

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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.

Appendices

Appendix E-1

AC flood frequency memo (20/09/2023)

Auckland Council

Memo

20/09/2023

To: Debbie Fellows, Matt Howard

cc: Jin Lee, Nicole Li, Ross Roberts

From: Kris Fordham

Subject: **GUIDELINES ON THE USE OF AGS2007 FOR LANDSLIDE RISK ASSESSMENT IN AUCKLAND FOLLOWING THE 2023 FLOODING AND CYCLONE**

INTRODUCTION

It is anticipated that the use of the AGS2007 guidelines will form a core part of the risk assessment process for recovery in Auckland. This guidance has been developed to support practitioners in implementing the AGS guidelines by providing location and event specific information and advice, along with lessons learned from earlier implementations.

This guideline will be revised regularly as more information becomes available, and as new lessons are learned.

Risk assessment is expected to be undertaken on a site-specific basis. Nothing in this document relieves the person undertaking the risk assessment of their obligations to properly assess the conditions at each location and to make an assessment relevant to the site. These general guidelines may support this process, but deviation from the guidelines is to be expected where conditions dictate.

DERIVING PROBABILITY OF A LANDSLIDE OCCURRING

In the 2007 update of the AGS guidelines, it was noted that some practitioners were incorrectly deriving indicative probability values for risk to life analysis. The 2000 version Appendix G Likelihood table was being used from left to right; that is a descriptor was selected from the description (or even by preference for the descriptor), and then the indicative probability assigned accordingly. This method is wrong. The Likelihood Table was reordered to indicate the correct sequence of logic from left to right and as discussed in section C5.4.2, an estimate of the probability should be made based on apparent performance, trigger probabilities etc, and then the descriptor assigned accordingly.

The tables provided in Appendix C of AGS2007c should be used from left to right; use Approximate Annual Probability or Description to assign Descriptor, not vice versa.

GENERAL CONSIDERATIONS FOR RAINFALL ARI

Short-term vs Long-term risk

In many cases there will be a requirement to assess the short-term risk (for the purposes of RBA placarding and building occupation) and the long-term risk (for risk categorisation and consenting if remedial works are required).

Short-term considerations

Short-term risk (nominally 1 year) will not need to consider the potential for climate change to increase the frequency of high-intensity rainfall. However, consideration should be given to the extremely wet 2023 summer which has led to unusually high groundwater levels. This could mean that landslides are more likely than normal in smaller rainfall events.

Long-term considerations

Long-term risk (nominally 100 years) should consider the potential for climate change to increase the frequency of high intensity rainfall.

More information on this can be found:

- In a summary of Auckland climate projections prepared by NIWA (2018): **https://knowledgeauckland.org.nz/media/1171/tr2017-031-2-auckland-region-climate-change-projections-and-impacts-summary-revised-jan-2018.pdf**

- In a technical paper: **https://www.nzgs.org/libraries/climate-change-sustainable-development-and-geotechnical-engineering-a-new-zealand-framework-for-improvement/**

ASSESSING THE ARI OF THE CYCLONE GABRIELLE EVENT - MURIWAI

Based on the best available data from rain radar, the rain experienced during Cyclone Gabrielle in Muriwai was >100-year event at a 12-hour duration.

This was a significant event for the region which came off the back of a significant "wet" period, including the event on the 27th of January 2023.

In Muriwai there are two sources of rainfall data available for analysis.

1. Physical TB3 tipping bucket rain gauge.
2. Auckland Councils Quantitative Precipitation Estimate (QPE) Rain Radar System.

TB3 tipping bucket rain gauge.

Unfortunately, during Cyclone Gabrielle, the tipping bucket rain gauge at Muriwai failed and was inundated by flood waters. This event record presented below in
Figure 1 is compromised as a result but provides an indication of the rainfall intensities at Muriwai prior to the site failing.
Prior to the gauge failing (01:15 am on the 14th), the gauge had recorded 129mm of rain with a peak 6-hour total of 88mm of rain, which is >20-year event (TP108, Auckland design rainfall depths).

Due to the missing record and the site being inundated during the event, this record is not recommended to be used to describe the event.

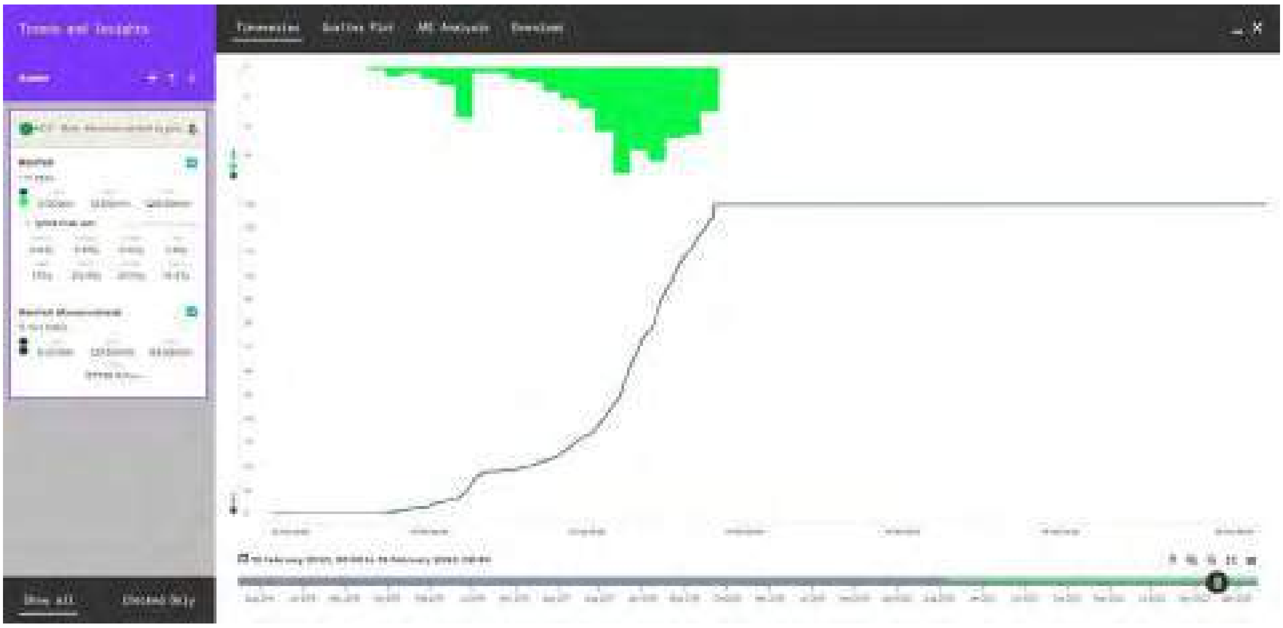

Figure 1: Muriwai TB3 tipping bucket rain gauge hourly totals and cumulative total. (note, the event is missing data from 01:15am 14th February due to being inundated)

Quantitative Precipitation Estimate (QPE) Rain Radar System.

The QPE rain radar system is a real-time rainfall product which utilises the Metservice radar (reflectivity), which is transformed using a relationship to rainfall depths based on the tipping bucket gauge network. The result is spatially representative rainfall depths across the region, as shown in **Figure 2**.

This product enables full, region wide analysis of extreme rainfall events in catchments where rain gauges are not located and when a gauge fails, as in the case with the Muriwai gauge.

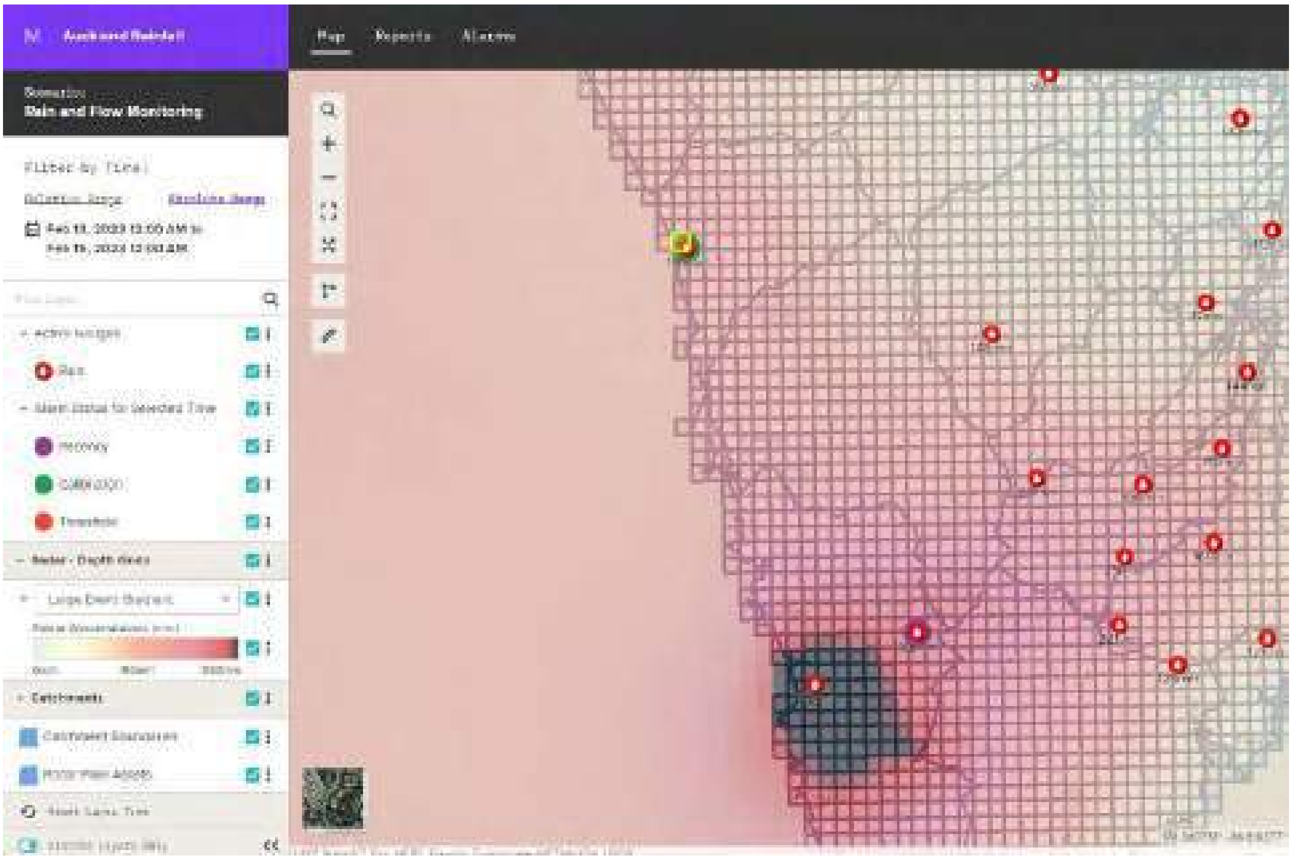

Figure 2; QPE Rain radar depth accumulations 13 February 2023 to 15 February 2023. The yellow grid location is the rainfall at the raingauge location at Muriwai

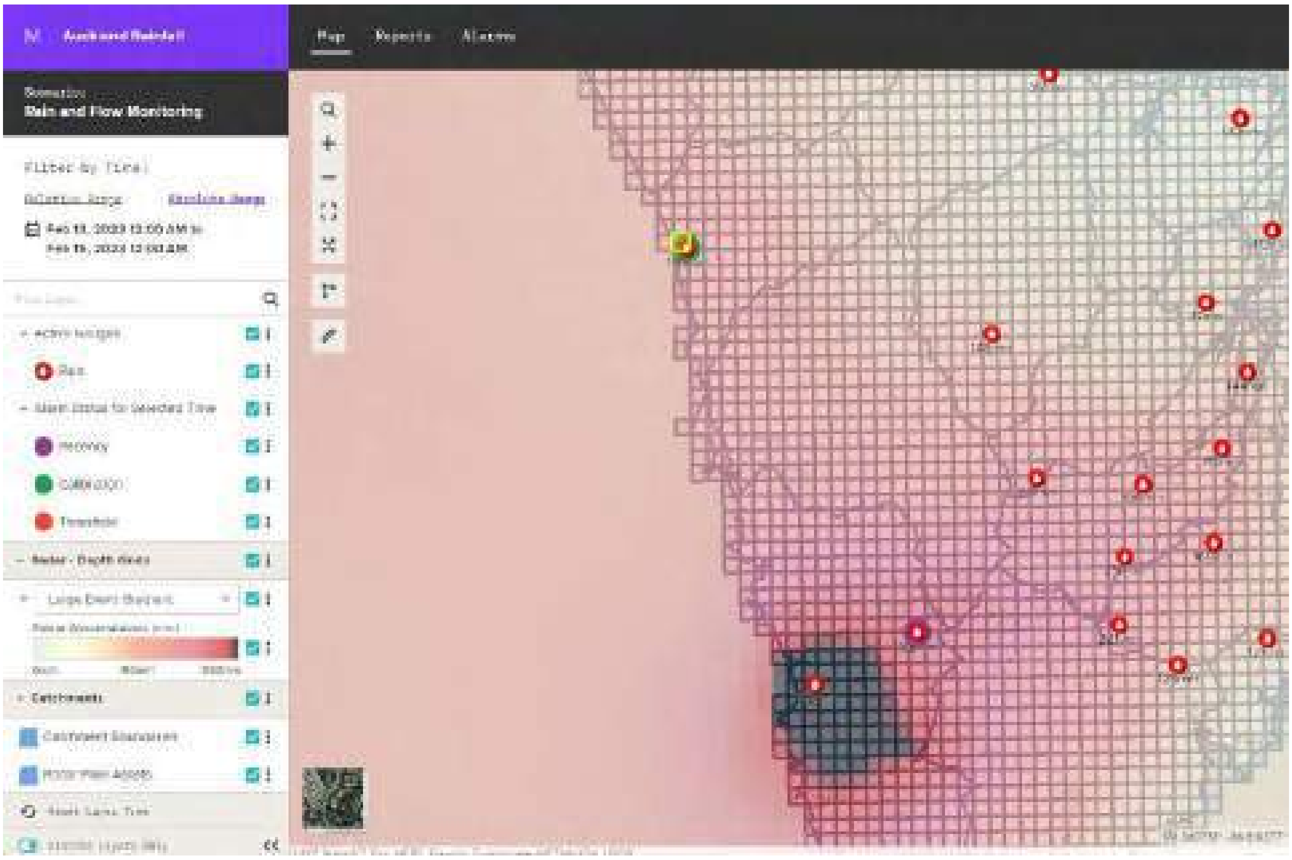

Figure 3: QPE Rain radar depths in Muriwai 13 February 2023 to 15 February 2023

Figure 4 below shows the Depth-duration-Frequency curve for the QPE grid location at Muriwai. The X-axis shows duration, y axis shows depth in a given event, and the curves show the expected rainfall depths for a range of ARIs from 2 to 100-year return period (TP108, Auckland design rainfall depths).

What happened during the event is plotted in purple. This analysis and the figures in table 1 shows that the peak rainfall total during the event of 146.9mm occurred over 12-hour period. This total is >100-year event at a 12-hour duration.

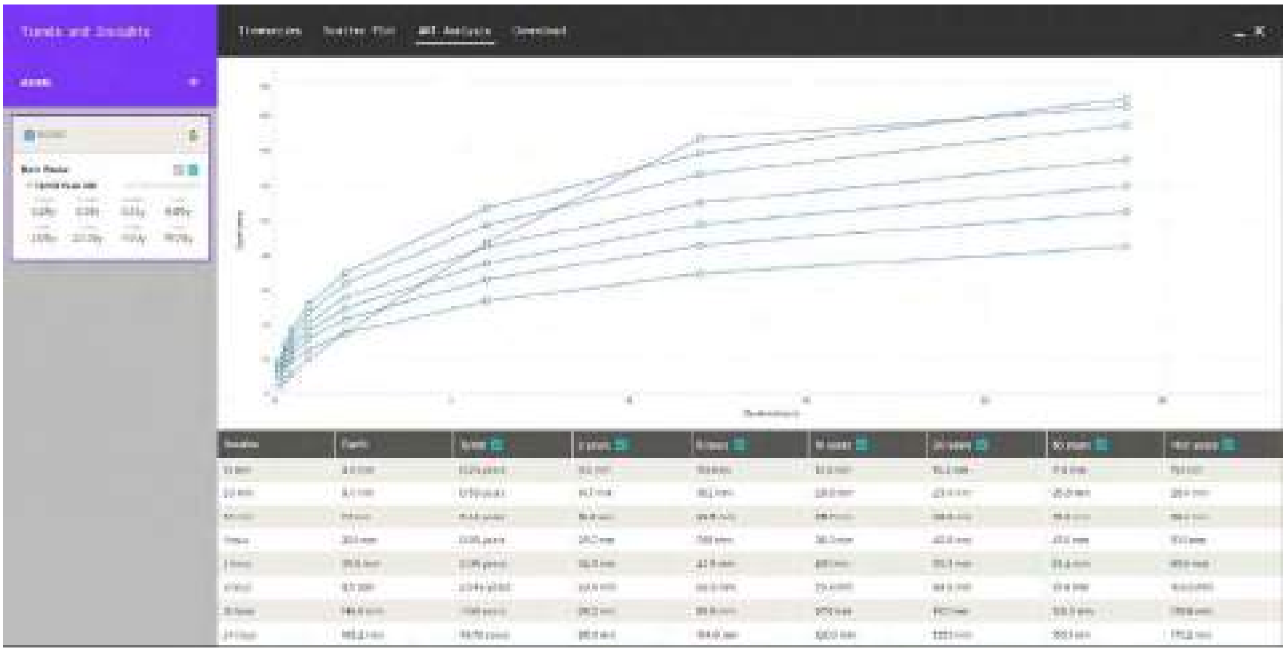

Figure 4: Depth-duration-Frequency curve for the QPE grid location at Muriwai (90767).

Table 1: Depth-duration-table for the QPE grid location at Muriwai (90767).

Duration	Depth	Tp108
10 min	4.3 mm	0.28 years
20 min	8.4 mm	0.38 years
30 min	11.1 mm	0.44 years
1 hour	20.1 mm	0.85 years
2 hour	35.0 mm	2.05 years
6 hour	87.1 mm	23.46 years
12 hour	146.9 mm	>100 years
24 hour	165.2 mm	79.78 years

Table 2: Depth-duration table from NIWA (HIRDSv4) including 250-year return period, with the 12-hour duration highlighted

Results

Site Details | Historical Data | RCP2.6 Scenario | RCP4.5 Scenario | RCP6.0 Scenario | RCP8.5 Scenario

Rainfall depths (mm) :: Historical Data

ARI	AEP	10m	20m	30m	1h	2h
1.58	0.633	10.7	13.9	16.2	21.2	27.6
2	0.500	11.7	15.1	17.6	23.0	30.1
5	0.200	14.9	19.3	22.5	29.4	38.5
10	0.100	17.2	22.3	26.0	34.1	44.6
20	0.050	19.5	25.3	29.6	38.8	50.6
30	0.033	20.9	27.1	31.7	41.6	54.5
40	0.025	21.9	28.4	33.2	43.6	57.1

Conclusions

The above information suggests that for the 12-hour duration rainfall the ARI is >100 years, and may be in the order of 250 years. However, the calculation above the 100-year assessment becomes increasingly unreliable, primarily because of the relatively short rainfall record available in New Zealand.

For the other durations modelled, the rainfall was below the 100-year event.

2023 Rainfall and antecedent conditions

The rain experienced in the Auckland region since the 1st of January 2023 has been historically significant.

During the period from the 1st of January to the 15th of February, 491mm of rainfall has fallen at Muriwai. Compared to the average rainfall for Muriwai for January of 70mm, indicates just how much rain has fallen at this location.

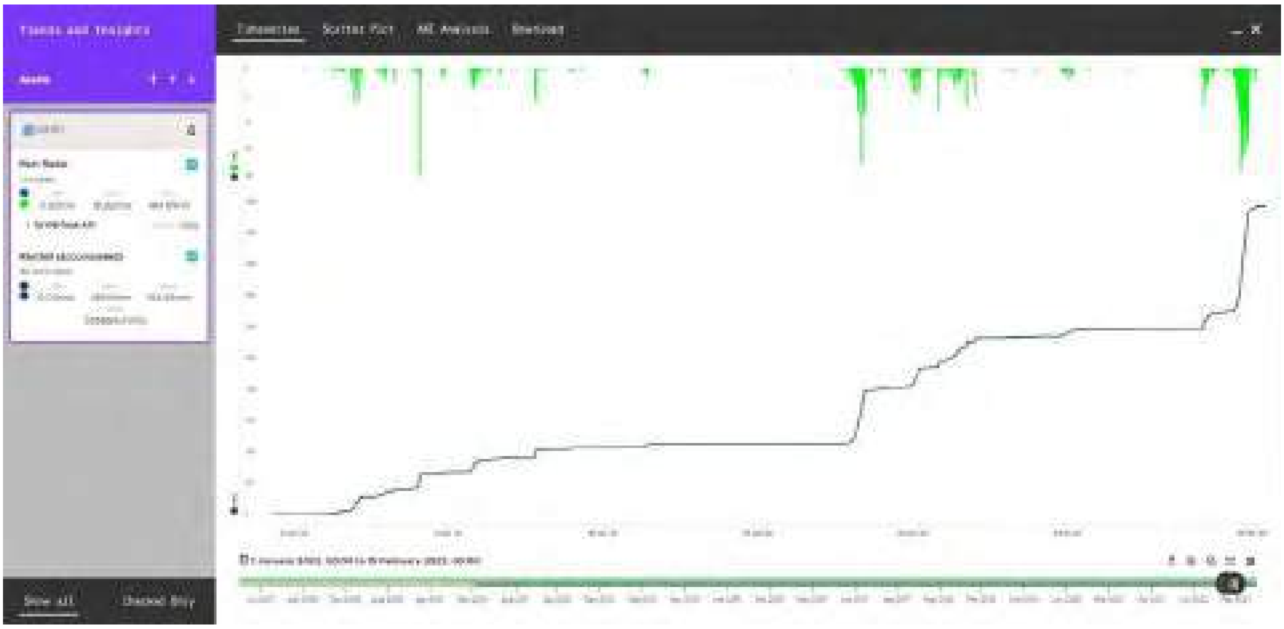

Figure 5: QPE Rain radar depths in Muriwai 1 January 2023 to 15 February 2023

Caveats

This interpretation is using data sampled from the rain gauges that doesn't include the statistics from the recent events that Auckland has experienced – the theory is that including these events in the record will shift and change the return periods and depth for all of Auckland.

Auckland Council have commissioned NIWA to undertake the analysis to re-run HIRDS 4 for Auckland to include the recent 3 years of extreme rainfall data – the results of this are expected by November 2023.

Recommendations

There are several different methods to extrapolate return periods which will all give very different and uncertain results.

It is recommended that for reporting purposes that an envelope of "risk" is determined as the ARI figures will change over time. In general for Muriwai it is considered reasonable to consider the event to be in the range of 100-250 year ARI.

For long-term risk assessment a 20% increase in rainfall intensity over the period has been projected by NIWA. A simplistic assessment (without climate modelling input) suggests this would change a 250-year ARI event to a 50-year ARI event. Risk assessment should consider both the current and future risk by re-calculating the risk taking into account this increased frequency.

For short-term risk assessments consideration should be given to the anticident ground saturation that is likely to persist at least through the winter of 2023.

ASSESSING THE ARI OF THE CYCLONE GABRIELLE EVENT – PIHA & KAREKARE

Based on the best available data from rain radar, the rain experienced during Cyclone Gabrielle in Piha was >100-year event at a 6-hour duration.

This was a significant event for the region which came off the back of a significant "wet" period, including the event on the 27th of January 2023.

In Piha there are two sources of rainfall data available for analysis.

1. Physical TB3 tipping bucket rain gauge.
2. Auckland Councils Quantitative Precipitation Estimate (QPE) Rain Radar System.

TB3 tipping bucket rain gauge.

During Cyclone Gabrielle, the tipping bucket rain gauge at Piha recorded 349.5mm of rain. This event record is presented below in **Figure 6**

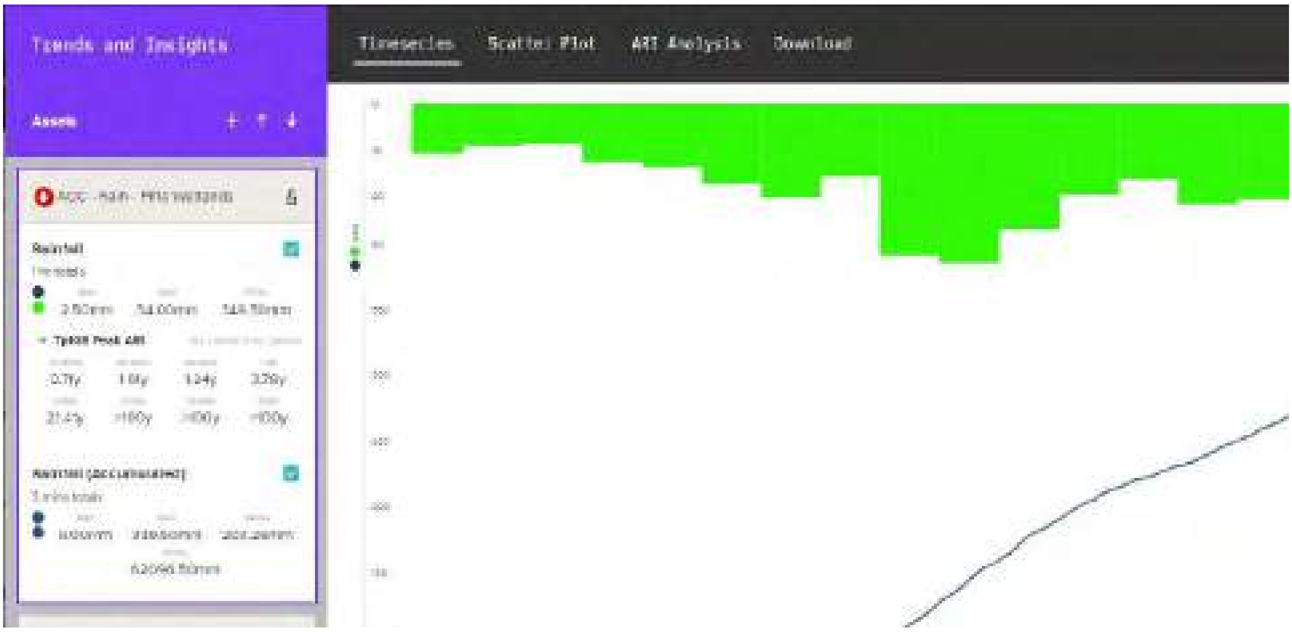

Figure 6: Piha TB3 tipping bucket rain gauge hourly totals and cumulative total

Quantitative Precipitation Estimate (QPE) Rain Radar System.

The QPE rain radar system is a real-time rainfall product which utilises the Metservice radar (reflectivity), which is transformed using a relationship to rainfall depths based on the tipping bucket gauge network. The result is spatially representative rainfall depths across the region, as shown in figure 7. This product enables full, region wide analysis of extreme rainfall events.

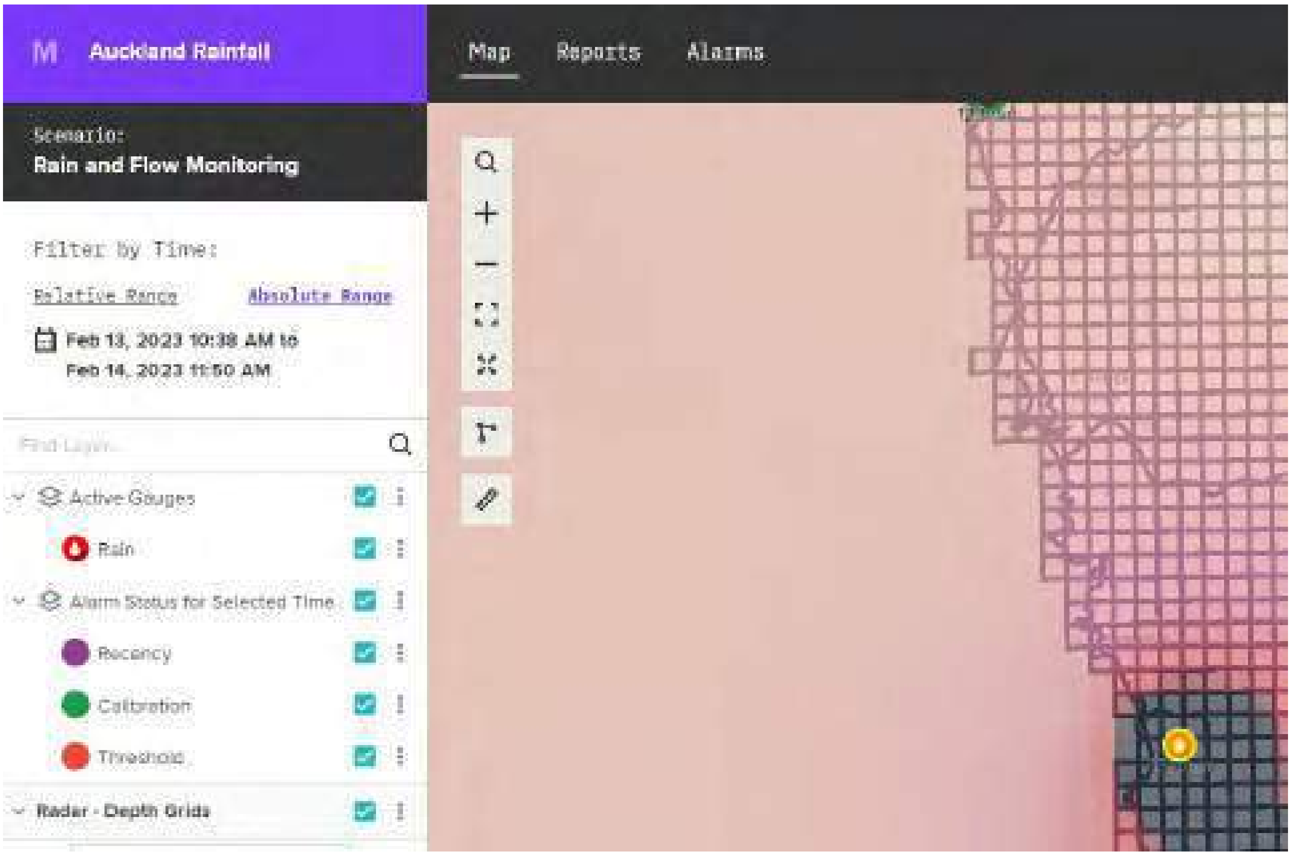

Figure 7: QPE Rain radar depth accumulations 13 February 2023 to 15 February 2023. The yellow grid location is the rainfall at the rain gauge location at Piha

Figure 8: QPE Rain radar depths in Piha 13 February 2023 to 15 February 2023

Figure 9 below shows the Depth-duration-Frequency curve for the QPE grid location at Piha. The X-axis shows duration, y axis shows depth in a given event, and the curves show the expected rainfall depths for a range of ARIs from 2 to 100-year return period (TP108, Auckland design rainfall depths).

What happened during the event is plotted in purple. This analysis and the figures in table 3 shows that the rainfall total exceeded the 100-year event from a 6 to 24 hour duration.

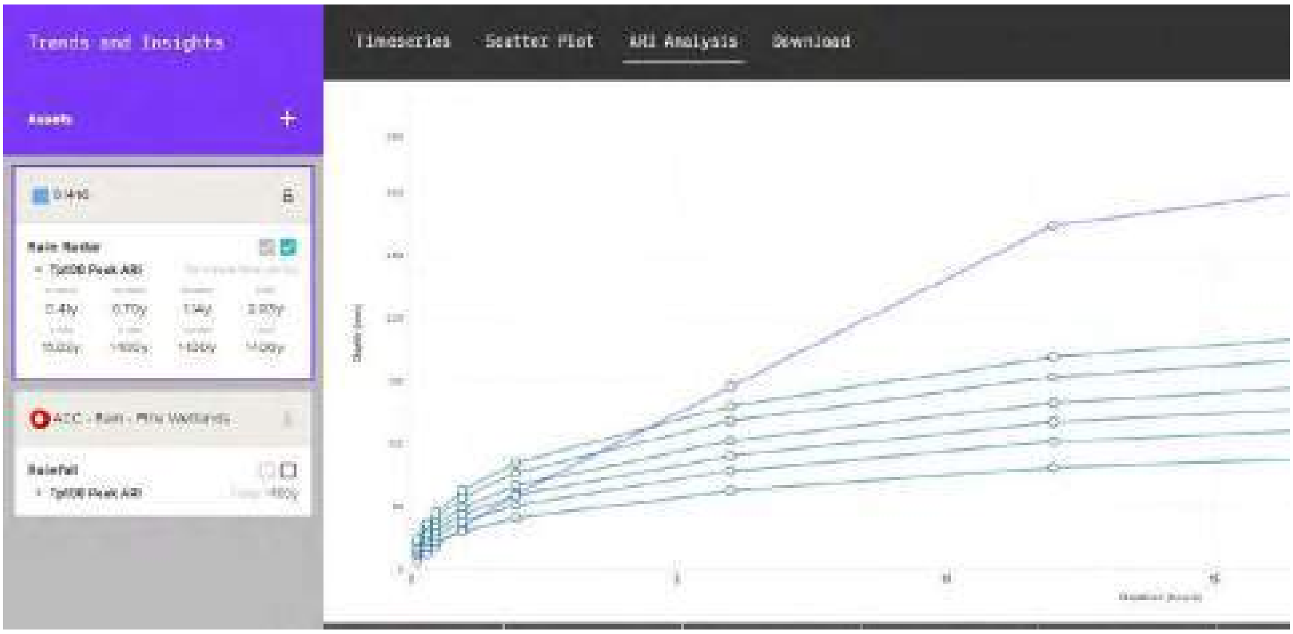

Figure 9: Depth-duration-Frequency curve for the QPE grid location at Piha (91416).

Table 3: Depth-duration-table for the QPE grid location at Piha (91416).

Duration	Depth
10 min	6.3 mm
20 min	12.2 mm
30 min	18.0 mm
1 hour	33.4 mm
2 hour	60.0 mm

Table 4: Depth-duration table from NIWA (HIRDSv4) including 250-year return period.

Results

Site Details | Historical Data | RCP2.6 Scenario | RCP4.5 Scenario | RCP6.0 Scenario | RCP8.5 Scenario

Rainfall depths (mm) :: Historical Data

ARI	AEP	10m	20m	30m	1h	2h
1.58	0.633	11.8	15.5	18.1	23.3	29.7
2	0.500	12.9	16.9	19.7	25.4	32.4
5	0.200	16.4	21.5	25.1	32.4	41.4
10	0.100	18.9	24.9	29.1	37.6	48.1
20	0.050	21.5	28.3	33.1	42.8	54.8
30	0.033	23.0	30.3	35.5	45.8	58.8
40	0.025	24.1	31.8	37.2	48.1	61.7

Conclusions

The above data suggests that for the 6 to 24-hour duration the ARI is >100 years and may be in the order of 250 years. However, the calculation above the 100-year assessment becomes increasingly unreliable, primarily as a result of the relatively short statistical rainfall records available in New Zealand.

For the other durations modelled, the rainfall was below the 100-year event.

2023 Rainfall and antecedent conditions

The rain experienced in the Auckland region since the 1st of January 2023 has been historically significant.

During the period from the 1st of January to the 15th of February, 704 mm of rainfall has fallen at Piha. Compared to the average rainfall for Piha for January of 70mm, indicates just how much rain has fallen at this location.

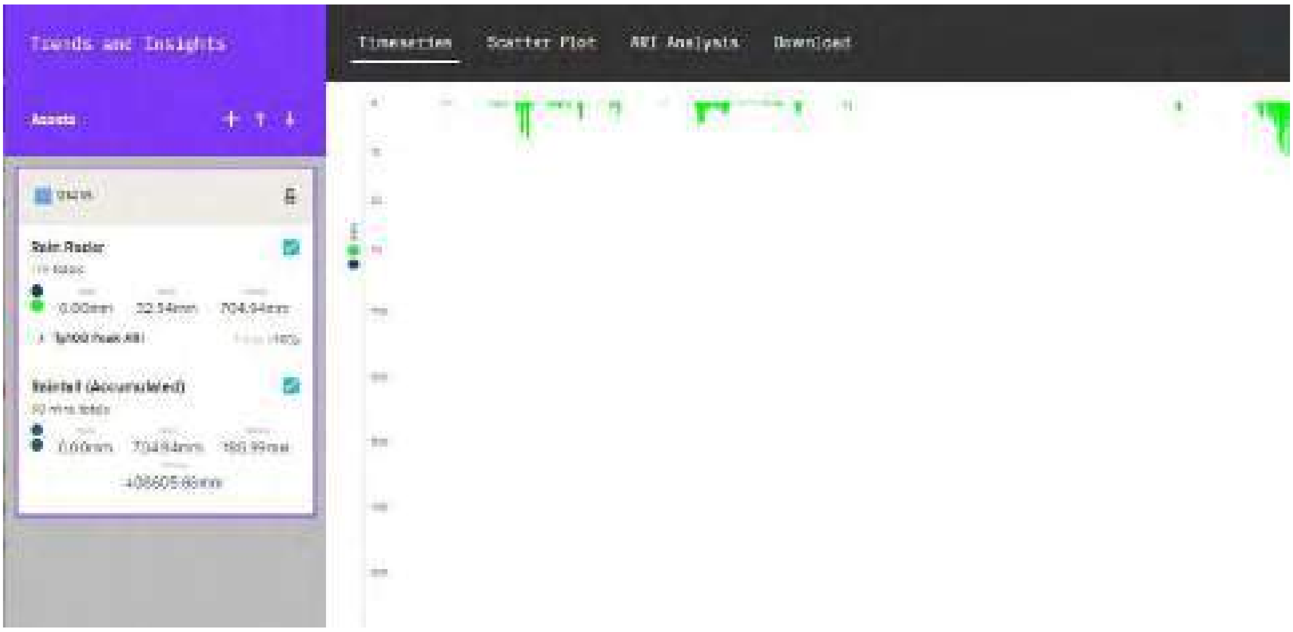

Figure 10: QPE Rain radar depths in Piha 1 January 2023 to 15 February 2023

Caveats

This interpretation is using data sampled from the rain gauges that doesn't include the statistics from the recent events that Auckland has experienced – the theory is that including these events in the record will shift and change the return periods and depth for all of Auckland.

Auckland Council have commissioned NIWA to undertake the analysis to re-run HIRDS 4 for Auckland to include the recent 3 years of extreme rainfall data – the results of this are expected by November 2023.

Recommendations

There are several different methods to extrapolate return periods which will all give very different and uncertain results.

It is recommended that for reporting purposes that an envelope of "risk" is determined as the ARI figures will change over time and as these events are incorporated into the statistical record. In general, for Piha it is considered reasonable to consider the event to be in the range of 100-250 year ARI.

For long-term risk assessment a 20% increase in rainfall intensity over the period has been projected by NIWA. A simplistic assessment (without climate modelling input) suggests this would change a 250-year ARI event to a 50-year ARI event. Risk assessment should consider both the current and future risk by re-calculating the risk considering this increased frequency.
For short-term risk assessments consideration should be given to the antecedent ground saturation that is likely to persist at least through the winter of 2023.

ASSESSING THE ARI OF THE AUCKLAND ANNIVERSARY FLOODS – CENTRAL AUCKLAND

Auckland experienced its largest ever rain event on the 27th January 2023. The majority of urban Auckland received rainfall in excess of the 100 year event. Thousands of houses and commercial buildings were inundated with floodwater.

Extreme rainfall was widespread across the region, with a wide front tracking in a southerly direction from the Northeast, impacting the Hibiscus Coast, North Shore, West, and Central Auckland before passing to the South of the Auckland Region.

While the rain was widespread across the region, including reported flooding in the Northern and Southern Rural areas, it was our urban city catchments which bore the brunt of the event and have experienced significant flooding issues.

Regionally there are two sources of rainfall data available for analysis.

1. Physical TB3 tipping bucket rain gauge.
2. Auckland Councils Quantitative Precipitation Estimate (QPE) Rain Radar System.

TB3 tipping bucket rain gauge.

Rainfall totals during the period from 00:00am Friday 27/01/2023 to 07:00am Saturday 28/01/2023 were in excess of 230mm at many locations across the region's urban extents, with the maximum recorded total during this period being 318mm. Most of the rain fell in a 4 hour period. The Onehunga @ Harbourside rain gauge measured 146 mm of rainfall in a 2-hour period, the average total rainfall for January is 73.8mm.

Table 5: Summary rainfall statistics by stormwater operational area 12am 27 Jan to 7am 28 Jan

	Total (00:00 27 Jan 07:00 28 Jan) mm		**1 Hour Total mm**	
	Max	Average	Max	Average
North	284	193	75	46
Central/West	286	217	91	50
South	263	163	75	32

Summary figures are calculated from all rain gauges in each of the 3 sub-regional areas. i.e., the max is the rain gauge in each area with the highest total for the event. The average is the average rain across all the rain gauges in that sub region. For example, in North there are 25 rain gauges which were averaged to get 193mm

Quantitative Precipitation Estimate (QPE) Rain Radar System.

The QPE rain radar system is a real-time rainfall product which utilises the Metservice radar (reflectivity), which is transformed using a relationship to rainfall depths based on the tipping bucket gauge network. The result is spatially representative rainfall depths across the region, as shown in **Figure 11**.

This product enables full, region wide analysis of extreme rainfall events.

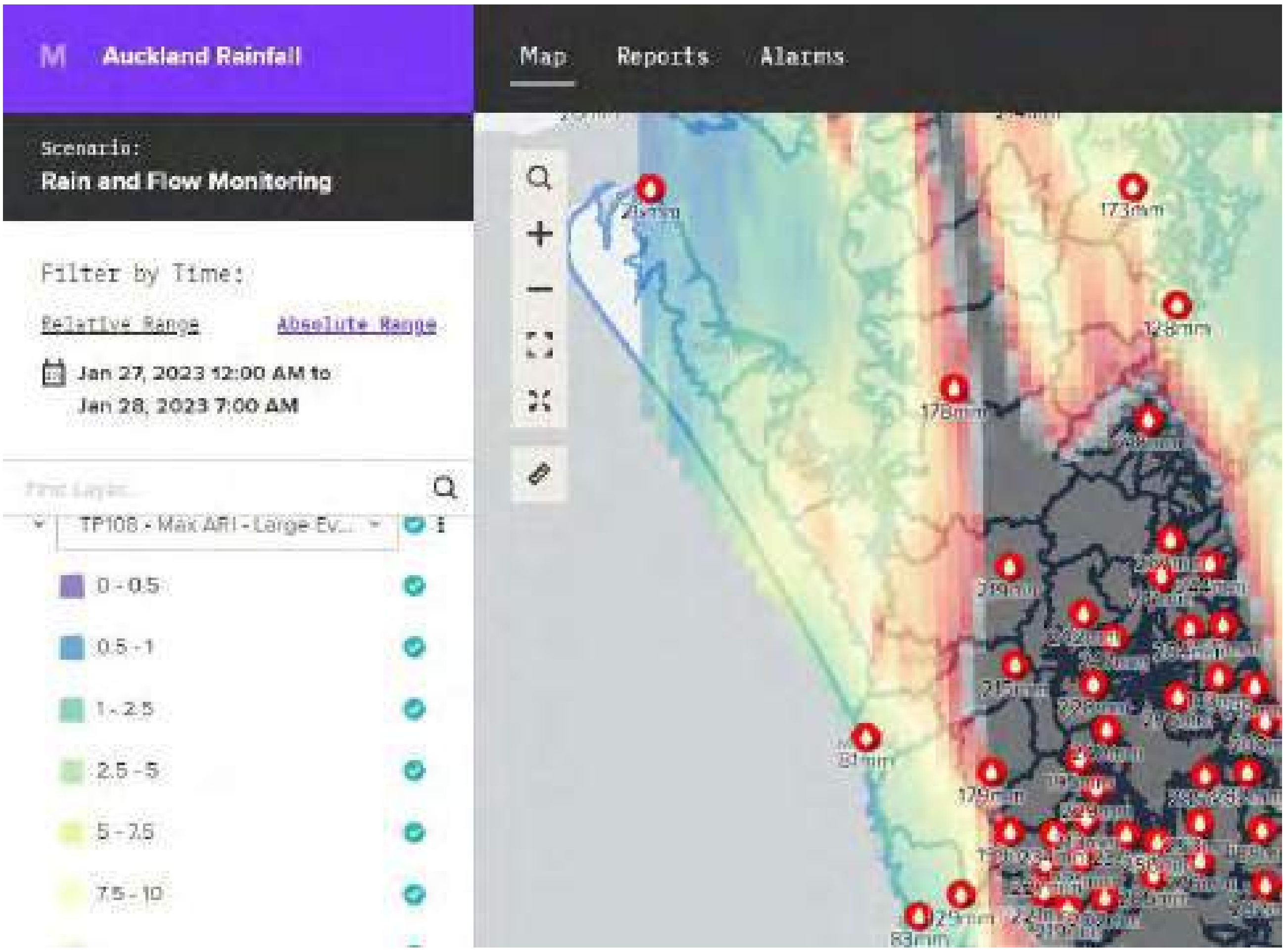

Figure 11: Recorded Rainfall Radar Max Average Recurrence Interval (ARI). The black area is where rainfall was greater than a 100yr ARI (for any of the 10,20,30 min and 1,2,6,12,24-hour durations) In the black area the event was greater than 100yr for the vast majority of durations.

Conclusions

The above data suggests that for the majority of the region the ARI for this event is >100 years and may be in the order of 250 years. However, the calculation above the 100-year assessment becomes increasingly unreliable, primarily because of the relatively short statistical rainfall records available in New Zealand.

Further analysis of this event by NIWA (https://niwa.co.nz/news/auckland-suffers-wettest-month-in-history) highlights the extreme nature of this event, indicating that this event could be described a “at least a 1-in-200-year event”.

Caveats

This interpretation is using data and models sampled from rain gauges that doesn't include the statistics from the recent events that Auckland has experienced, the theory is that including these events in the record will shift and change the return periods and depth for all of Auckland.
Auckland Council have commissioned NIWA to undertake the analysis to re-run HIRDS 4 for Auckland to include the recent 3 years of extreme rainfall data – the results of this are expected by November 2023.

Recommendations

There are several different methods to extrapolate return periods which will all give very different and uncertain results.

It is recommended that for reporting purposes that an envelope of "risk" is determined as the ARI figures will change over time and as these events are incorporated into the statistical record. In general, for the Auckland Anniversary floods it is considered reasonable to consider the event to be in the range of 100-250 year ARI.

For long-term risk assessment a 20% increase in rainfall intensity over the period has been projected by NIWA. A simplistic assessment (without climate modelling input) suggests this would change a 250-year ARI event to a 50-year ARI event. Risk assessment should consider both the current and future risk by re-calculating the risk considering this increased frequency.
For short-term risk assessments consideration should be given to the antecedent ground saturation that is likely to persist at least through the winter of 2023.

For further information or clarification of the figures presented please contact the undersigned.

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Appendix E-2

85 Domain Crescent Landslide Risk Assessment

Waitākere Coastal Communities Landslide Risk Assessment

85 Domain Crescent, Muriwai

Auckland Council

30 April 2024

→ **The Power of Commitment**

Project name	AC Geo Panel - Waitākere Coastal Communities LHRA
Document title	Waitākere Coastal Communities Landslide Risk Assessment | 85 Domain Crescent, Muriwai
Project number	12612462
File name	12612462- RiskAssess85 Domain MuriwaiFINAL.docx

Status Code	**Revision**	**Author**	**Reviewer**		**Approved for issue**		
			Name	**Signature**	**Name**	**Signature**	**Date**
S4	0	Ryan Hayes	Don Macfarlane		Matt Howard		30/04/2024
[Status code]							
[Status code]							
[Status code]							

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1. Introduction

1.1 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 turned into saturated debris flows as they travelled downslope. These flows 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 February 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).

GHD has been engaged by Auckland Council (AC)[1] to carry out landslide risk assessments and to provide associated landslide risk management advice and geotechnical investigations recommendations in the Waitakere area, specifically for the residential areas of Muriwai, Piha and Karekare. These assessments were necessary due to widespread, damaging landslides associated with Cyclone Gabrielle in February 2023. GHD has completed a landslide risk assessment[2], whereby some properties were identified as having an unacceptably high risk of being impacted by future large landslides.

1.2 Purpose of this report

The residential property at 85 Domain Crescent, Muriwai ('the site') has been assessed by GHD as having an acceptable risk from large scale landslides[3] (see the November 2023 report). However, a localised, damaging landslide has occurred, and the purpose of this assessment is to carry out a Quantitative Landslide Risk Assessment (QRA) to estimate the risk of Loss of Life to individuals at the property. The outcome of the QRA will be used to inform subsequent property risk categorisation and building placard designation review by AC.

1.3 Scope

The scope of work requested by AC is as follows:

– Review available historical and recent imagery including LiDAR.
– Review pertinent historical data and GHD work undertaken as part of the wider Muriwai landslide risk assessment reported in GHD (November 2023).
– Undertake a site engineering geological assessment of landslide hazards at the impacted property.
– Undertake a QRA where landslide hazards have been identified that pose a Loss of Life landslide risk using the Australian Geomechanics Society Practice Note Guidelines for Landslide Risk Management, commonly known as AGS (2007c).
– Deliver report(s) documenting the QRA inputs and outcome.

Specifically excluded are an assessment of property risk, site specific subsurface geotechnical investigations, service inspections, and groundwater monitoring.

This assessment considers geotechnical matters only. There may be other non-geotechnical considerations that affect the final property risk categorisation or placard designation of which GHD are not aware, such as flood risk and structural damage to property.

[1] Under Contract CW198379, Master Services Agreement CCCS: CW74240 dated 7/09/2019
[2] Dated 03/11/2023, document file ref 12612462_Overall Report FINALRev0.docx
[3] In the GHD November 2023 report, 'large scale' landslide hazards refers to landslides originating from the main escarpment that typically have a volume of more than about 50 m3 with the potential to cause total or partial collapse of a dwelling.

Identification of options for the mitigation of geotechnical hazards has not been undertaken as part of this study.

Although considered unlikely, GHD reserves the right to amend the opinions, conclusions and recommendations provided within this report, should additional geotechnical information become available.

1.4 Our Approach

GHD have completed a landslide risk assessment for Muriwai which assessed the risk to life of large-scale landslide hazards to inform possible future dwelling hazard designations. The assessment was limited to 'large scale' landslide hazards originating from the main escarpment located to the south-east of Muriwai because the initial placard assessment was largely aimed at mitigating risks associated with these.

Smaller, more localised landslide hazards that could originate (or may have already initiated) from other areas in Muriwai such as within the footprint of individual residential properties were not considered in the risk assessment. However, these have the potential to cause damage to dwellings and subsequently pose a risk to life for residents, partly due to the relatively steep topography and the potential for high travel velocity.

The approach of identifying landslide hazards over large and common source areas, such as that used for the November 2023 Muriwai assessment, does not capture numerous, smaller scale landslides. For this reason, a QRA is presented for the individual property (85 Domain Crescent) based on an assessment of the site that includes site observations and a desktop review of available information. The results aid with informing the QRA with regards to the presence of existing and historical landslide hazards and site-specific slope conditions.

The QRA undertaken for this report assesses risk to life to occupants of the dwelling. The assessment considers a number of hazard scenarios as follows:

1. the **most likely significant landslide hazard** based on the observed hazards with respect to the mapped landslides and their distribution within the broader landscape. In addition, considerations of the hazard relationship to topography, position on the hillslope and proximity to the elements at risk are also included. This represents a credible hazard scenario following a triggering event with a similar frequency as the February 2023 event.
2. Existing geohazards that have resulted from recent failures with the potential to pose risk to life, such as regression and/or remobilisation of translational failures that are upslope or downslope of a dwelling or failure of oversteepened fill and cut slopes. These represent hazards that exist at the site and may be initiated by a more frequent triggering event.
3. Other possible geotechnical slope instability hazards that have potential to pose a risk to life such as failures of fills, cuttings and failed retaining walls. These also represent hazards that may be triggered by a more frequent event.

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. The methodology used for the QRA is outlined in Appendix A. The site-specific input parameters and uncertainties are described in Section 3.

A glossary of terminology is presented in Appendix B.

2. Site conditions

2.1 Site description

The site is located at 85 Domain Crescent, Muriwai, legally described as Lot 64 DP 39644 and it has an approximate area of 845 m^2. A GHD engineering geologist inspected the site on 11 December 2023. No inspection was undertaken within or under the house, however, an insurance assessment report that was made available to us by AC provides photos of the interior[4].

As shown in Figure 2.1, the affected property is located on the lower portion of the approximately 80 m high main escarpment that is aligned to the northeast and separates the township between lower-lying plateaus to the west (near sea level), and higher areas to the south and east. Locally, the main escarpment extends from Domain Crescent at its base at an elevation of approximately 60 m RL, to Oaia Road at its crest at an elevation of approximately 150 m RL. The slopes encompassing the site have an average slope angle of approximately 32°.

The dwelling is a three-storey structure that sits on timber poles and it is located near the base of the slope, adjacent to Domain Crescent. The building platform may have been modified to accommodate the structure, and the dwelling is accessed via a concrete driveway. A steep (generally 30-40°) natural, vegetated slope behind the dwelling extends to an elevation of approximately 100 m above sea level, where it meets a prominent north-trending ridgeline at the eastern extent of the property boundary.

Two 'large' landslides (mapped on Figure 2.1) originating to the west of the site occurred during Cyclone Gabrielle but did not affect the dwelling. A third, smaller scale, localised failure originating from within the property boundary at approx. 83 m RL developed into a debris flow which impacted the rear of the dwelling causing structural damage.

One of the large-scale failures originating on slopes at higher elevations above the site (approx. 120 m RL) developed into a channelised debris flow reaching Domain Crescent. Silt discharge from the debris partially inundated the elevated timber deck on southern side of the dwelling.

[4] Tonkin + Taylor, 19 June 2023. Claim for Natural Disaster (Landslip) Damage Sarah Gerritsen, 85 Domain Crescent, Muriwai, Auckland, 0881 EQC/Insurer Claim Number C90154866

Figure 2.1 *Site location along Domain Crescent*

2.2 Site services and sources of water

Auckland Council's GeoMaps presents relevant underground services and hydrologic information for the site. An excerpt of the data is presented in Figure 2.2.

Two overland flow paths are mapped to the north and south of the property boundary originating at approximately 105 m RL and 75 m RL, respectively, connecting approximately 50 m downslope, west of the dwelling. Both overland flow paths have a catchment size of approximately 2000 m^2 – 4000 m^2.

The travel paths of the debris associated with the two large scale landslides above the site, to the north and south, appear to correlate with the mapped overland flow paths.

No underground services associated with water are mapped on the slopes above the dwelling.

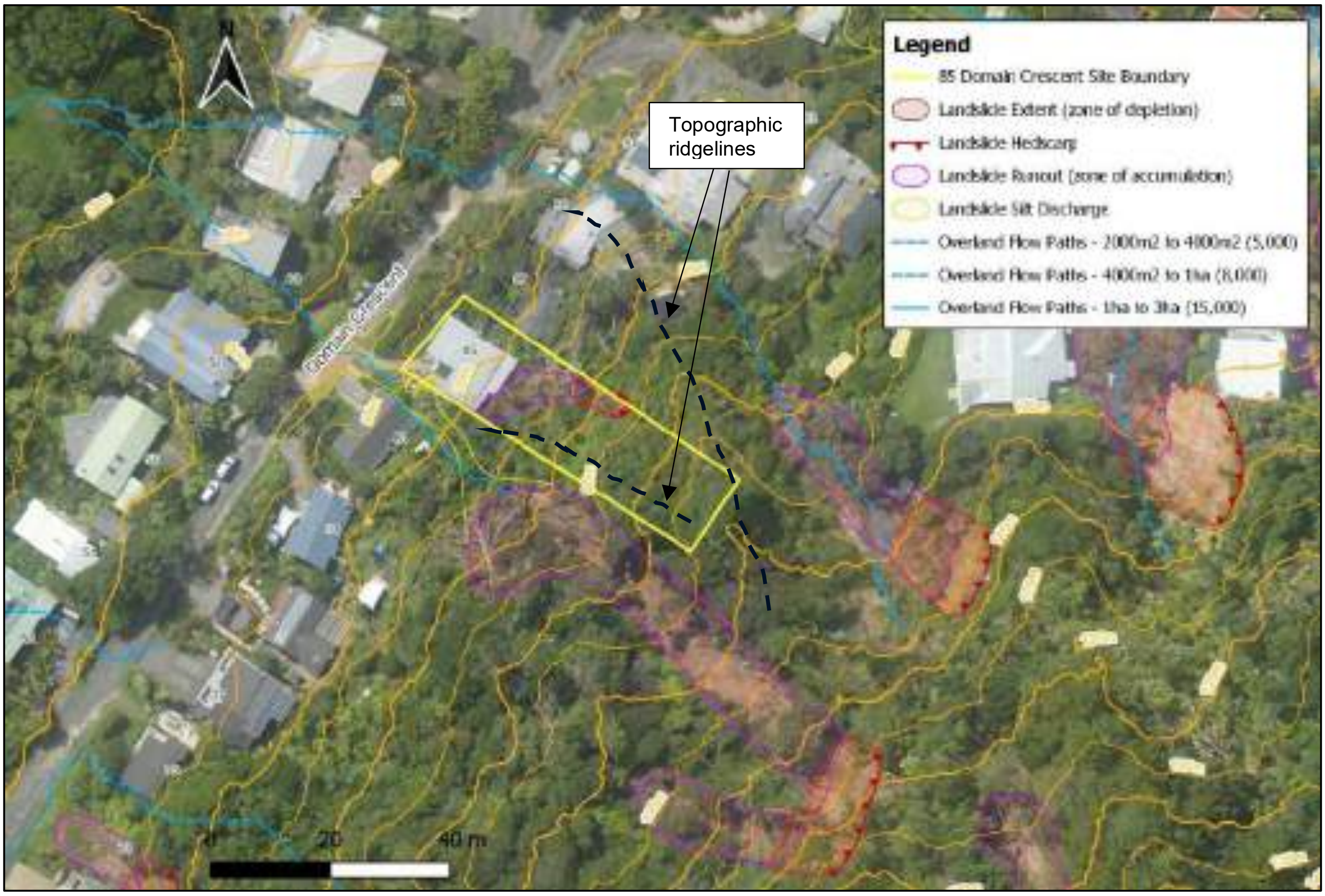


Figure 2.2 Overland flow paths and underground services for the site (source: Auckland Council GeoMaps).

2.3 Published geology

The published 1:50,000 scale geological map of the area (Hayward, 1983) indicates the site is entirely underlain by the Awhitu Sand Formation (mp), part of the Kaihu Group (Figure 2.3).

Awhitu Sands ('qs') are Pliocene aged (less than 2 Mya) characterised as 'coarse sand, clayey, often limonitised (as laterally discontinuous layers), with minor tuff, lignite and siltstone' (Hayward, 1983). The formation originated as coastal sand deposits. Awhitu Sands are generally oxidised to an orange-brown colour when exposed at the surface, resulting in a weak iron-cementation that allows for the development of large, more than 50 m high steep slopes, such as the escarpment.

The formation is weakly bedded and cross-bedded at the sub metre scale. Locally the formation is inferred to dip north and eastward at a shallow angle. Occurrences of silty/clayey horizons are occasionally visible in outcrop and have been encountered within boreholes, however it is unclear how persistent they are spatially.

Although not mapped, more recent colluvium material formed as a result of ongoing erosion and periodic landsliding associated with escarpment recession is likely present on the basal/lower slopes of the escarpment.

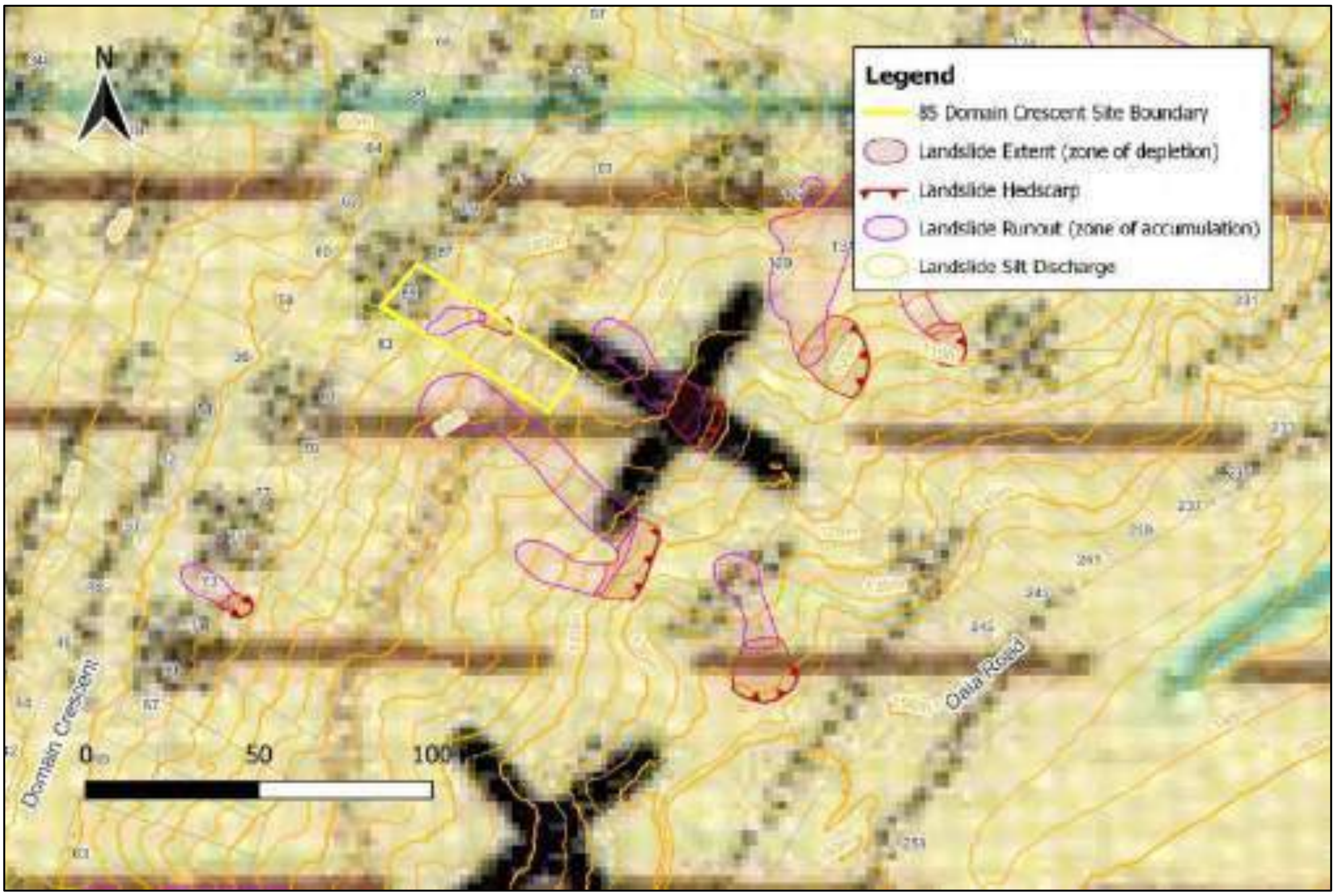


Figure 2.3 Excerpt of the Waitākere 1:50,000 scale geological map (Hayward, 1983[5]), illustrating the underlying geology at the site location.

[5] Hayward, B.W. 1983: Sheet Q11, Waitakere. Geological Map of New Zealand 1:50,000 Map

2.4 Historical data summary

A summary of the historical data relevant to 85 Domain Crescent is presented in Table 2.1.

Table 2.1 Summary of historical data

	Applicable data available	Notes
Historic aerial photos	- 1940 - 1950 - 1953 - 1975 - 2000 - 2004 - 2008 - 2010-2011 - 2015-2017 - 2022	- No obvious evidence of instability was identified from the historical aerials within the property itself. - Evidence of wider scale erosion evident from 1940, where many of the spurs leading off main escarpment are bare as well as section of the crest of the escarpment. Suggests ongoing erosion of surficial soil. No regression of escarpment observed. - Photos sourced from Retrolens and Auckland Council Geomaps.
NZ Geotechnical database	One borehole (BH-MH05) completed by GHD in August 2023. Located 15 m west of south-west corner of property boundary (see Figure 2.6).	- 10.95 m deep borehole. - 0 – 5.6 m: Ancient colluvial deposits generally comprising sandy silt and silty sand. - 5.6 – 10.95 m: Awhitu sand formation comprising variably cemented sand (medium dense to very dense)
Council GeoMaps	Overland flow data from Auckland City Council ArcGIS.	- Discussed in Section 2.2.
Rapid building Assessment Geotech reporting	N/A	N/A
Independent geotechnical reports	Soil & Rock Consultants (2001) report for proposed house extension. Babbage Consultants geotechnical appraisal advice (2000) Tonkin & Taylor (2023) EQC report	- Summarised in Table 2.2 below.
Anecdotal information	N/A	N/A
LiDAR Imagery	Feb 2023 Digital Terrain Model.	- Headscarps in the escarpment crest suggest ongoing recession through debris flows. - Headscarps also seen on smaller ridgelines extending down the escarpment. - Possible hummocky ground on the natural slopes above the dwelling on 85 Domain Crescent.

Table 2.2 Historical geotechnical reports summary

Geotechnical report	Relevant comments
Soil & Rock consultants – Geotechnical investigation for proposed extension to existing dwelling (Jan 2001)	- Evidence of shallow surface creep over the property with the formation of terracettes and the presence of hummocky ground on steeper slopes and shallow rooting trees frequently exhibiting downslope leaning. - No evidence of obvious large scale instability just shallow surface creep. - Local topography indicates that surface runoff from above the dwelling is concentrated into an overland flow path feature that runs through the southern corner of the property and continues through into the adjacent property to the southwest. - Four hand augers were completed to depths of 2.3 to 3.4 m encountered loose to medium dense sand silts and silty sands overlying dense to very dense (cemented) silts/sands. Subsurface interpretation of the site illustrated on Figure 2.4 below. - An inground barrier pile wall was recommended to support the proposed cut bench.
Babbage Consultants – Geotechnical appraisal and advice re: slip affecting 60 Domain Crescent (June 2000)	- Slopes below the road (Domain Crescent) failed, developing into a debris flow, leaving a 5-6 m high scarp. - Stormwater pipes observed protruding from scarp. - The cause of the slip likely water entry into the slope through the pipes. Progressive landslide movement may have restricted stormwater discharge. - No signs of movement observed affecting No. 85. The slopes above the house however clearly exhibiting evidence of periodic localised movement.
Tonkin & Taylor – Claim for Natural Disaster (Landslip) Damage (EQC report)	- Details property damage including damage to dwelling (racking and twisting entire building), inundation of deck and damage to services. - Determined that there is an imminent risk of regression of the landslip headscarp. - Recommended conceptual remedial works include; BioCoir matting over failed surface, hydroseeding, construction of a timber pole catch fence following removal of debris.

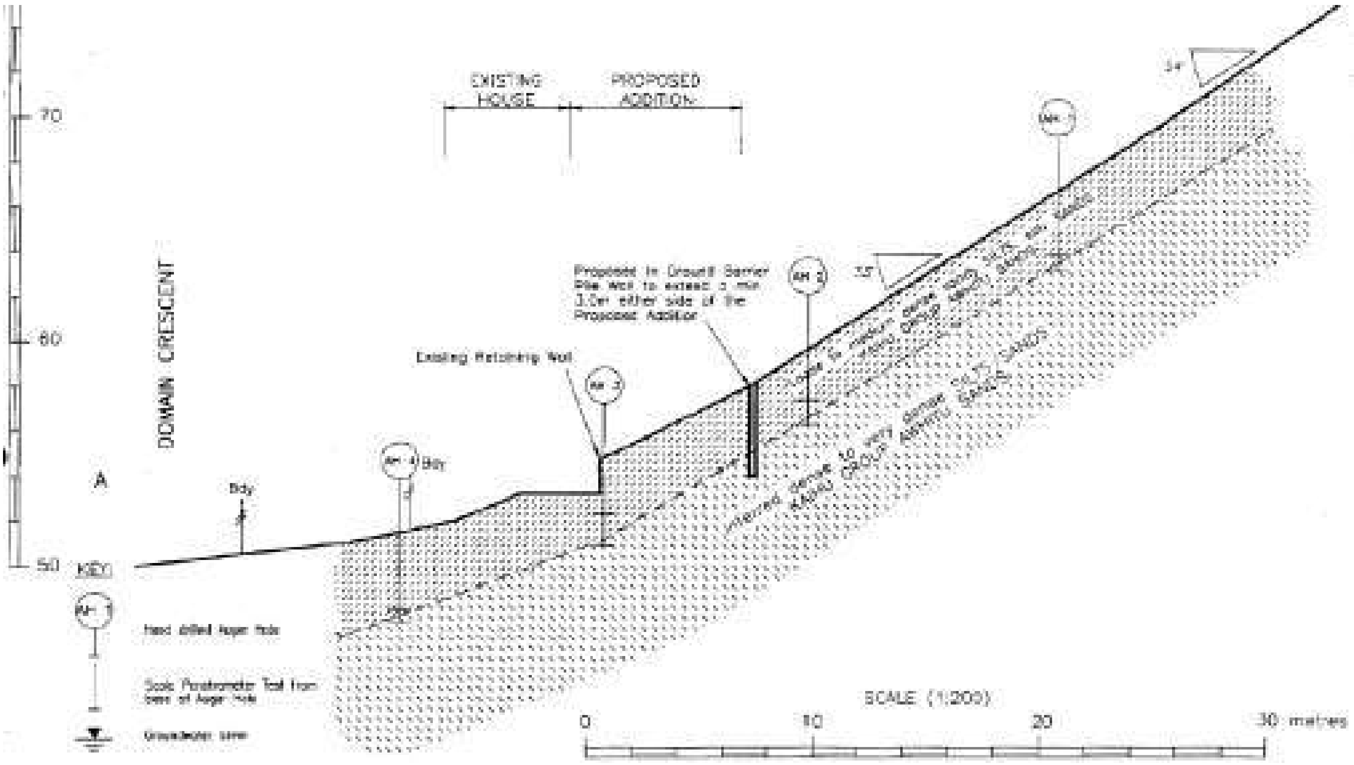


Figure 2.4 Interpreted geological cross section (Excerpt from Soil & Rock Consultants, 2001 (note: this report was issued for the proposed building which has since been constructed)

2.5 Engineering geological model

2.5.1 Awhitu Sand Formation

Awhitu Sands are exposed within the entire escarpment and have generally been described as medium dense to very dense sands overlying massive, extremely weak, moderately weathered, iron-cemented fine to coarse sandstone. Irregular layers of clay and silt rich material are typically spaced every 5-10 m and relatively thin (less than 1.0 m and often less than 0.1 m). The strength profile of the Awhitu Sands displays a relatively linear increase with depth.

The in-situ nature of the Awhitu Sands suggests they are relatively permeable. However, as discussed in the November report there is also significant evidence for perched groundwater tables shown by:

- Multiple occurrences of groundwater seeps or springs emerging within the middle and base of the escarpment slope face, from above underlying (presumed aquiclude) layers of clay and silt rich beds as well as heavily oxidised iron pans
- Variable and sharply changing weathering profile with localised layers of cemented iron oxidised sand between un-oxidised material at depth.

2.5.2 General landslide characteristics

As described in the November report (GHD 2023), the landslides identified across Muriwai following the February 2023 event can be categorised into two types based on their physical characteristics as follows:

Large slips: typical headscarp widths of 30-70 m, with source and debris runout areas more than 100 m in length, often extending well past the base of the escarpment onto the flatter slopes below, and

Smaller isolated slips: generally with headscarp widths of less than 30 m and extending less than 50 m. As a result debris from these landslides generally did not reach the base of the escarpment.

2.5.3 Landslide impacting the site

The landslide that occurred within the site is illustrated by site mapping on Figure 2.5 and is also shown in the context of different imagery on Figure 2.6 and Figure 2.7 below. An interpretive cross section prepared through the site is presented in Figure 2.12. Ground conditions have been interpreted from a combination of historical data, site mapping and nearby geotechnical investigation data. The cross section is indicative only and may not be representative of actual conditions.

The landslide headscarp (Figure 2.8) has an approximate width of 7 m and is approximately 10 m above the rear of the dwelling near the crest of a ridgeline. Following a high degree of ground saturation, it initiated on a 30-35° vegetated slope as a shallow (~ 0.5 m deep) translational failure (Figure 2.9) which developed into a debris flow, likely entraining additional material on its descent. The initial landslide source volume was approximately 20 m^3, increasing to approximately 60-80 m^3 following entrainment. The landslide impacted the rear of the dwelling (Figure 2.10). The resulting damage to the dwelling included widespread structural deformation (see Figure 2.11 and T+T, 2023) with no immediate building collapse. Inundation of the of the decking was also recorded, which, according to our mapping is likely a result of secondary silt discharge from the large-scale landslide that occurred to the south of the site.

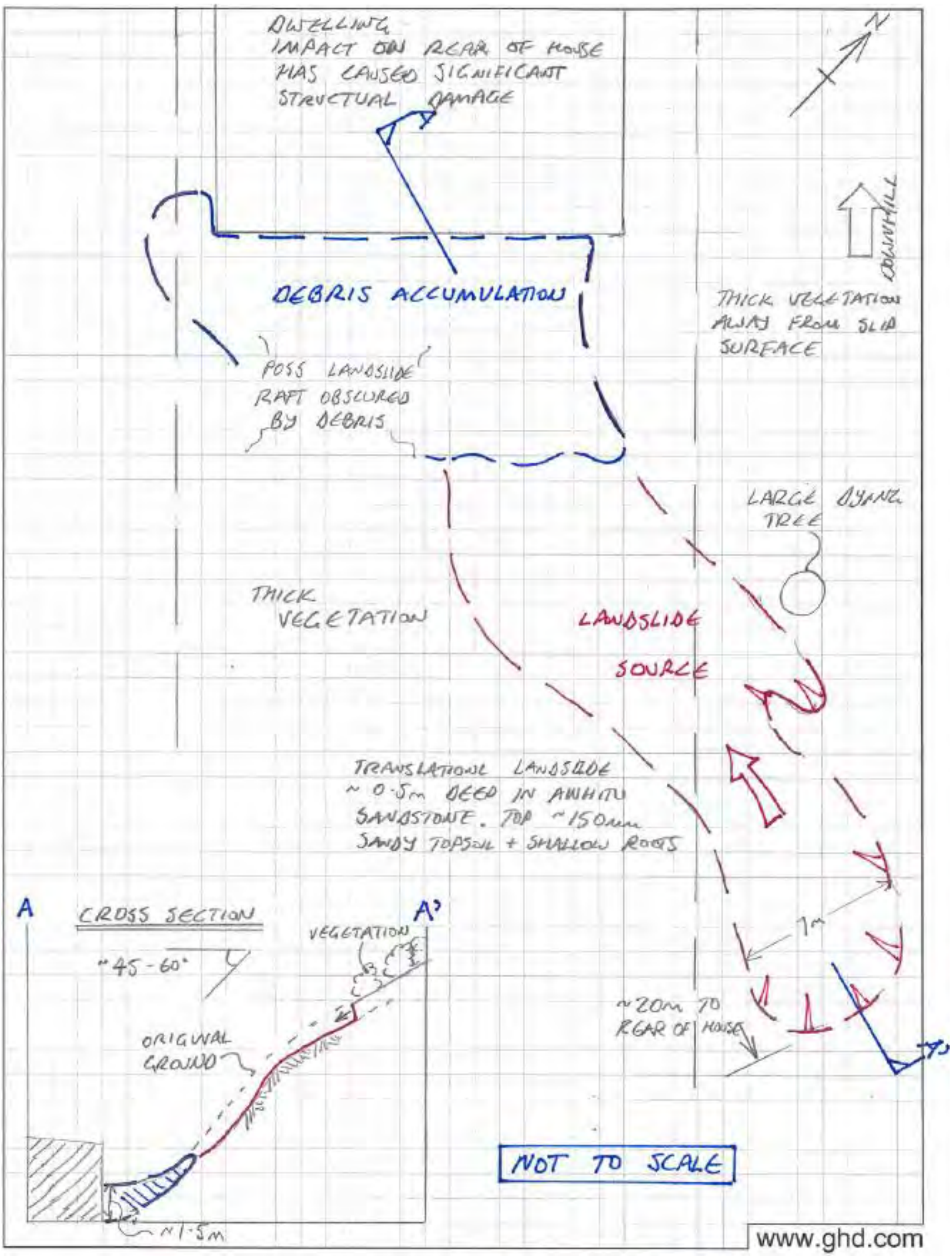


Figure 2.5 ***GHD site mapping of the landslide (completed 11 December 2023)***

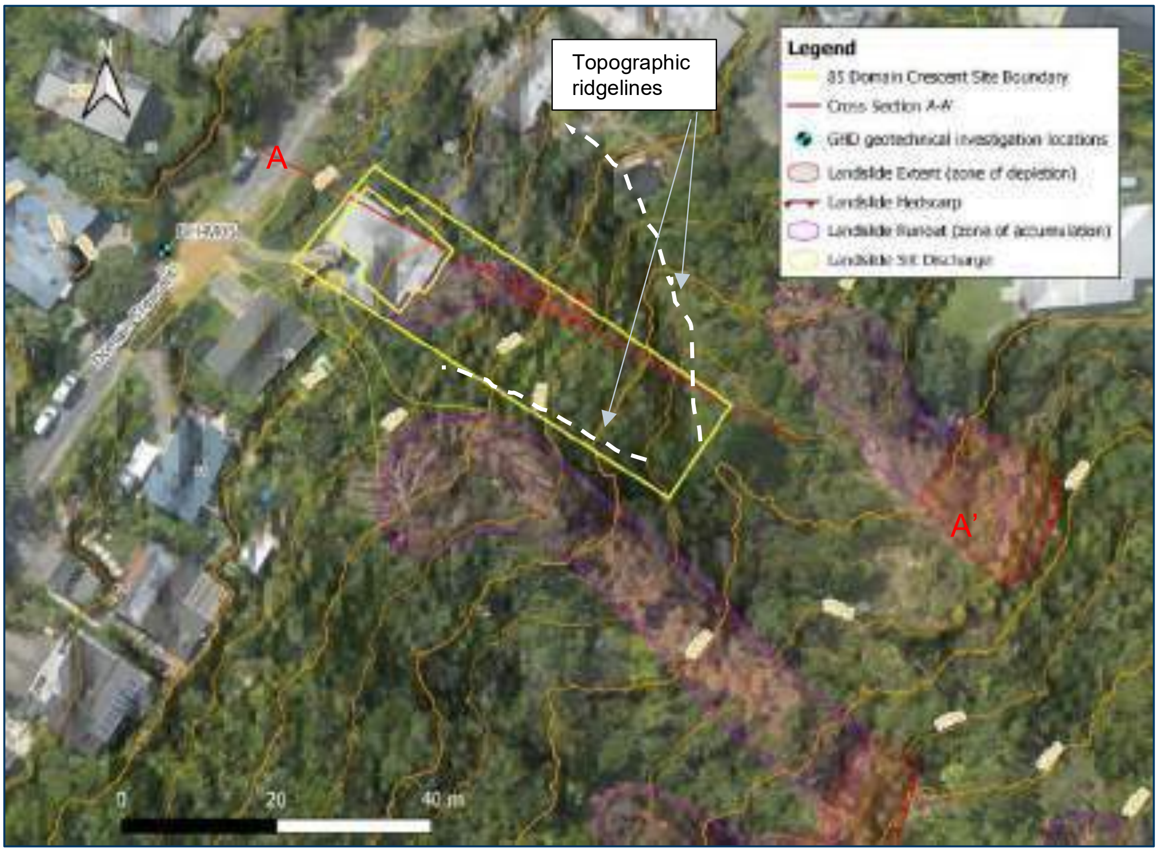


Figure 2.6 ***Landslide locations relative to the site shown on February 2023 aerial image.***

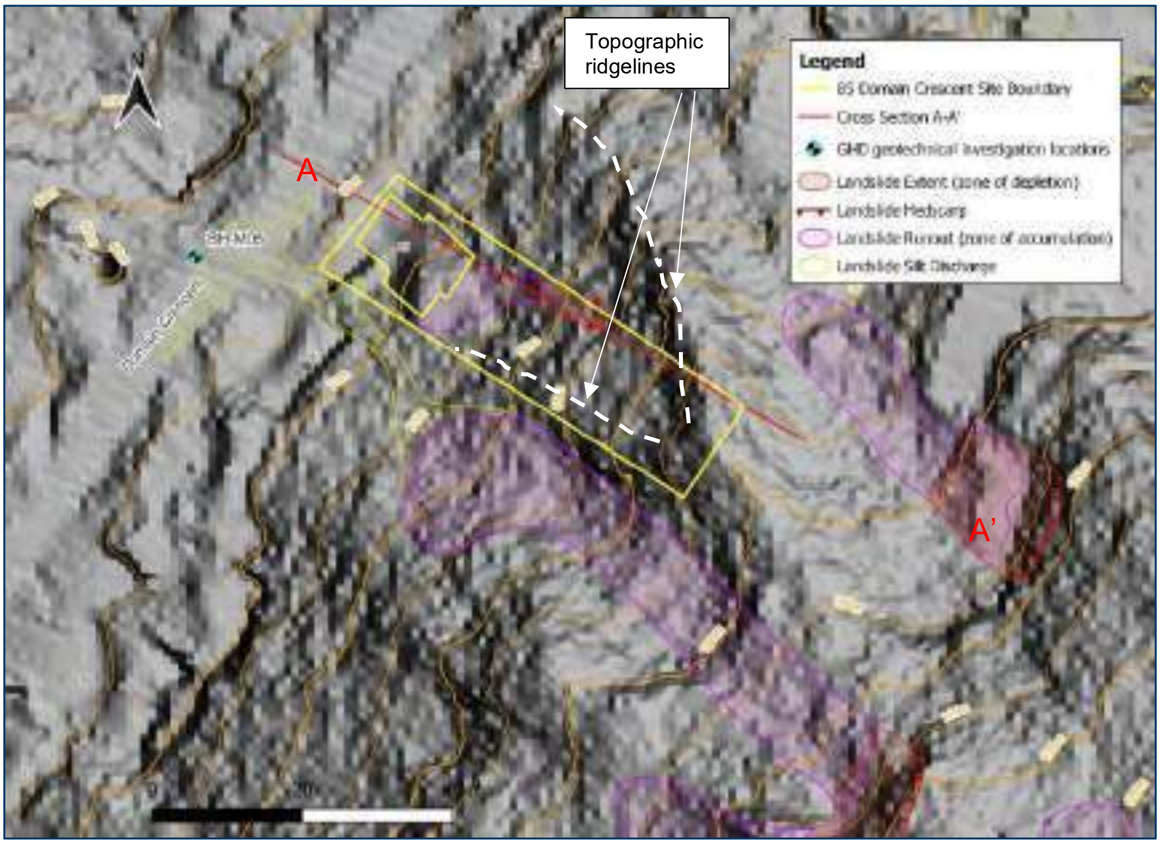


Figure 2.7 ***Landslide location relative to the site shown on LiDAR Hillshade (source: Auckland Council Feb 2023).***

Figure 2.8 **Exposed headscarp of landslide.**

Figure 2.9 **Failure surface (evacuated zone) exhibiting evidence of post failure erosion. Looking upslope.**

Figure 2.10 **Debris piled up at the rear of dwelling (estimated up to 1.5 m thick)**

Figure 2.11 **Damage caused by landslide includes racking of entire building (exhibited by bending of exterior wall)**

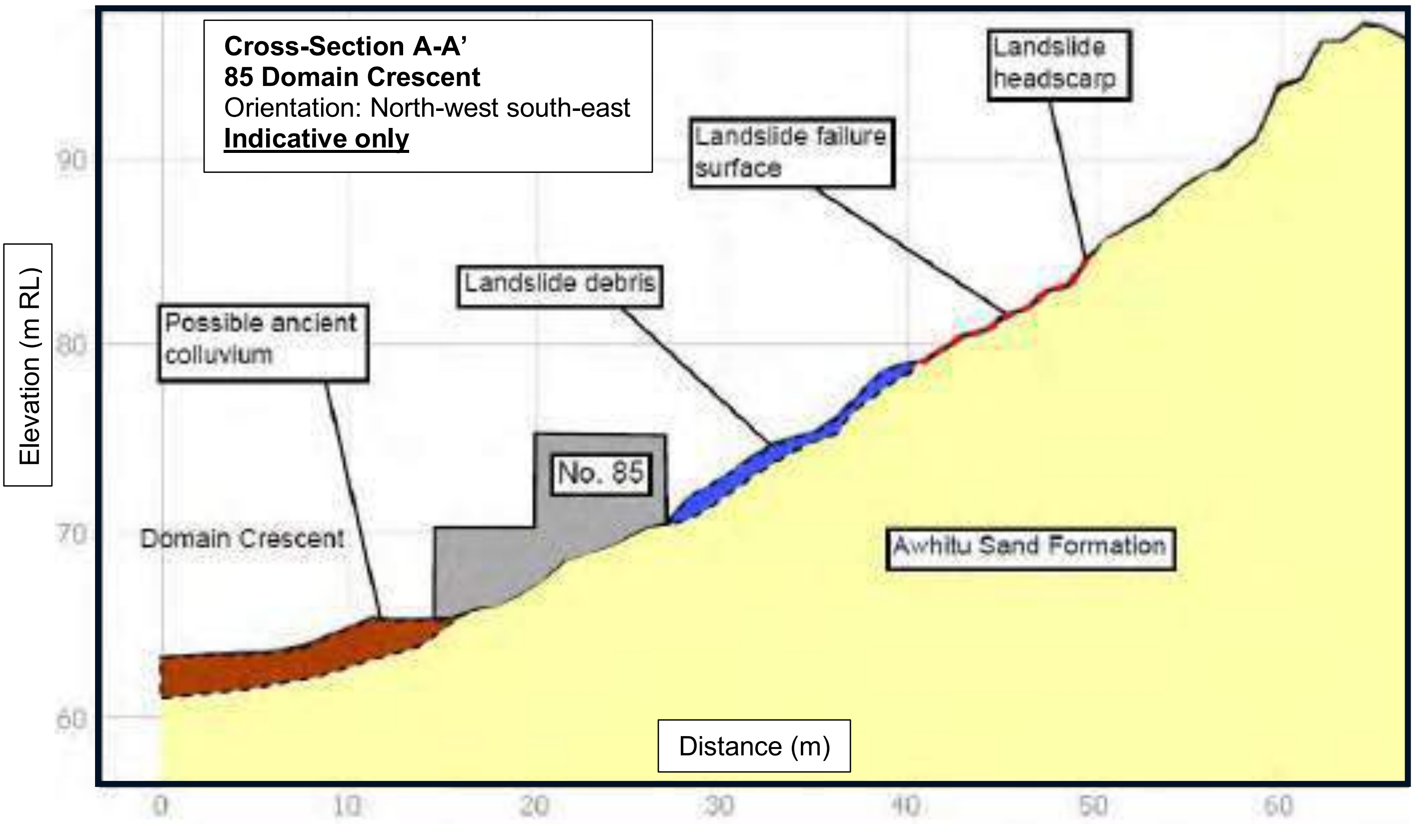


Figure 2.12 Indicative cross section A-A' through 85 Domain Crescent

3. Landslide risk estimation

The Australian Geomechanics Society Landslide Risk Management guidelines, published in 2007 and now commonly referred to as AGS (2007), have been adopted for the following unmitigated loss of life landslide risk assessment. Appendix A provides background information and guidance on how the methodology has been applied for assessing risk to life at the site.

The existing dwelling (or a new dwelling of similar construction occupying the same location) has been considered as the element at risk for this assessment. Our assessment assumes the recent landslide debris has been removed. Where appropriate, sensitivity checks have been undertaken for comparative purposes.

3.1 Hazard characterisation

The landslide hazards considered as part of this assessment are as follows:

– **LS1** (Landslide Hazard 1) – The most likely future landslide to occur somewhere on the slopes above the property. The landslide would be a shallow failure with a volume in the order of 40 m^3 that develops into a debris flow entraining additional downslope material. The assumed landslide characteristics have been inferred from observations of the previous failure and landslides to occur elsewhere in Muriwai. The possible source area considered for a future landslide above the dwelling, highlighted on Figure 3.1 and Figure 3.2 below, is constrained by two relatively prominent ridgelines.

– **LS2** (Landslide Hazard 2) – Regression of the existing landslide headscarp. This is likely to have a volume somewhat smaller than the landslide that occurred in February 2023.

3.2 Likelihood of landsliding ($P_{(H)}$)

The basis for estimating probability of occurrence for each landslide hazard considered as part of this assessment in provided in Appendix A and the probabilities adopted are provided below.

3.2.1 Likelihood of LS1

Two considerations of probability for occurrence for the most likely future landslide are:

– $P_{(H'1)}$ is the probability that the rainfall threshold for the most likely significant landslide is exceeded, which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or **0.01** (see analysis by AC in Appendix A) or 1 in 50 or **0.02** under the influence of future climate change.

– $P_{(H'2)}$ is the probability that a slope above the dwellings fails. A single landslide occurred on the slopes above the dwelling. Considering the total area of the slopes above the dwelling with similar conditions, and therefore considered susceptible to failure, an estimate of 5% failed during the February 2023 rainfall event. Given that a significant portion of the possible source area is directly above the dwelling, an increased value of $P_{(H'2)}$ **= 0.1** has been adopted.

3.2.2 Likelihood of LS2

Given the current condition of the exposed landslide headscarp, it is considered that regression of the existing landslide will occur in the same location during a relatively frequent rainfall event. A value of $P_{(H'1)}$ of **1 in 10** or **0.1** is adopted whilst $P_{(H'2)}$ is considered certain and a value of **1.0** is adopted.

3.3 Probability of spatial impact ($P_{(S:H)}$)

Our estimate of spatial probability is based on several factors which depend on the landslide hazards being considered and site-specific slope conditions. Our approach is detailed in Appendix A. Figure 3.1 and Figure 3.2

below provide an indication of the slope conditions at 85 Domain Crescent and the surrounding area (slope angles and inferred preferential flow paths, respectively).

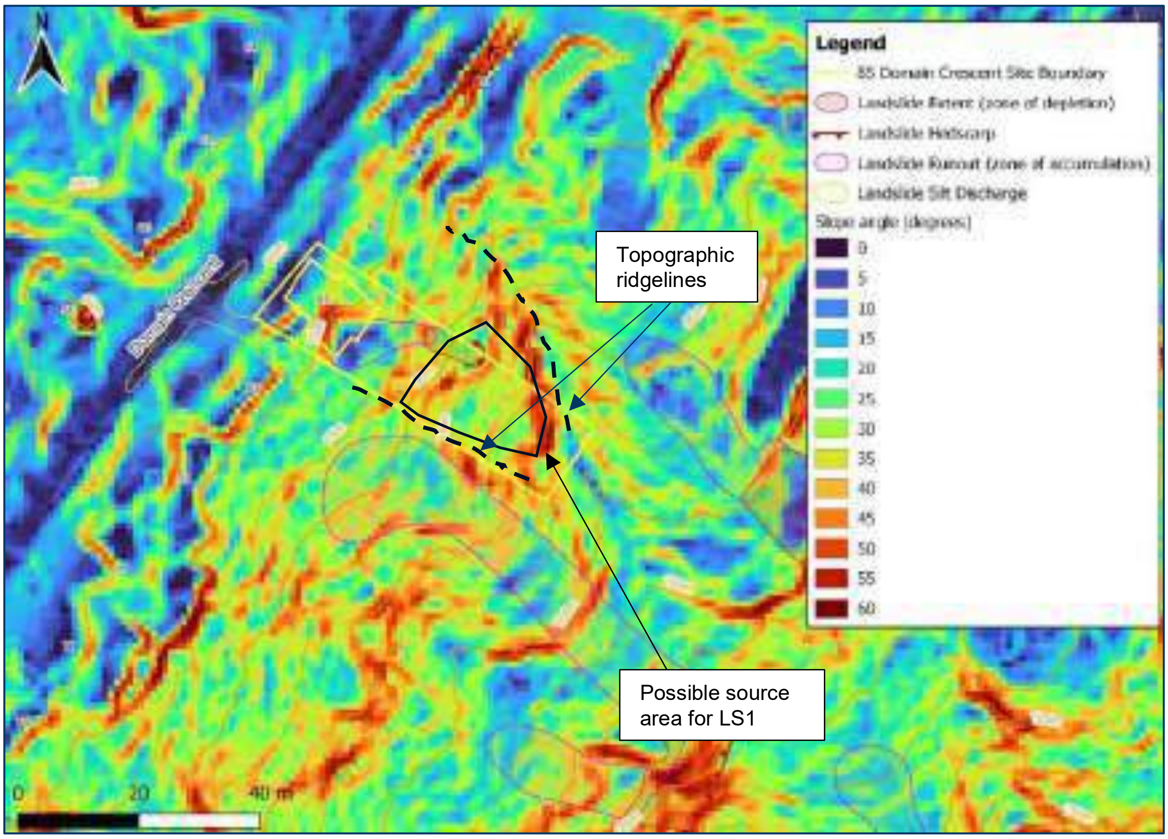


Figure 3.1 ***Slope map of 85 Domain Crescent and surrounding area. Slope angles based on 2023 DTM data.***

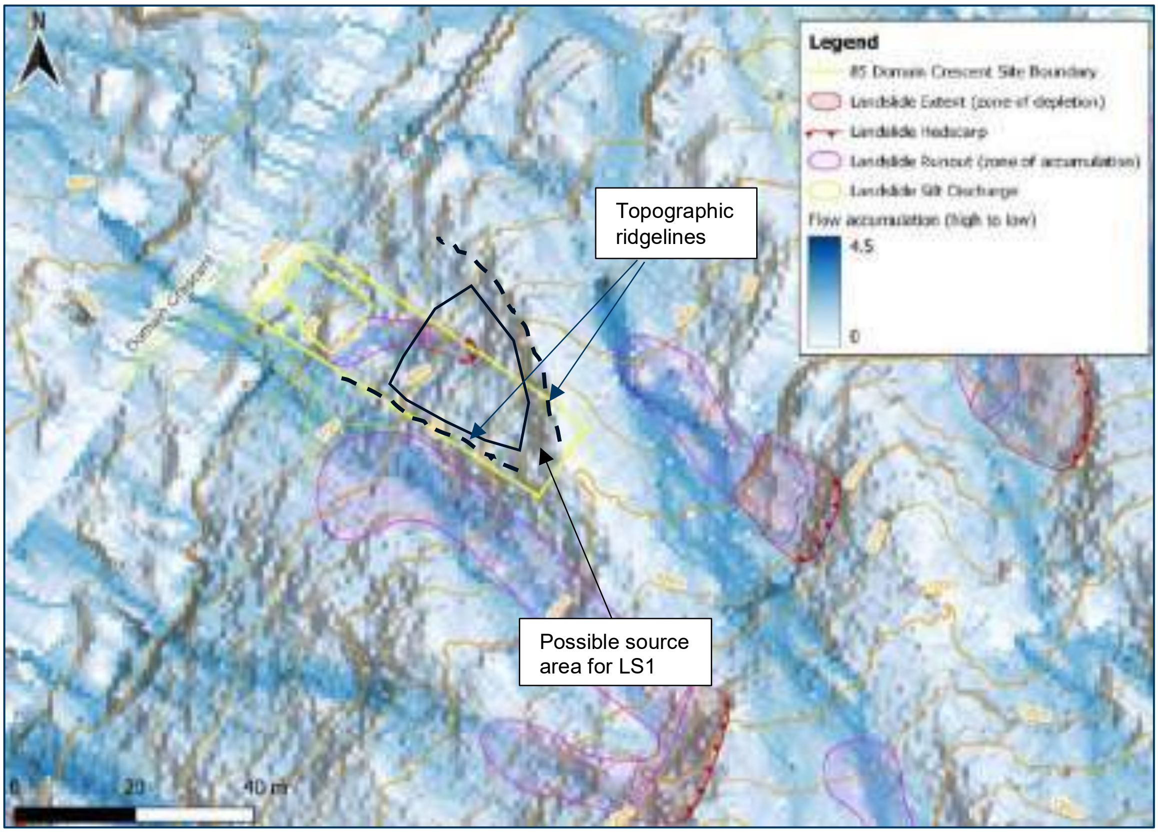


Figure 3.2 ***Flow accumulation map of 85 Domain Crescent and surrounding area. Indicates preferential flow path for surface water. Modelling based on 2023 DTM data.***

3.3.1 Probability of spatial impact (LS1)

Two conditional factors are considered for the most likely significant landslide:

- $P_{(S':H'1)}$ is the probability that if the landslide occurs it travels in the direction of the site. Based on the position of the dwelling at the base of a relatively planar slope exhibiting a somewhat concave geomorphology at its crest, a landslide initiating in the possible source area above the site (Figure 3.1) would likely travel downslope (northwest) towards the dwelling. Based on the flow accumulation plot (Figure 3.2) a landslide is unlikely to take a preferential flow path. A value of **1.0** is adopted.
- $P_{(S':H'2)}$ is the probability that if the landslide occurs it will reach the property. The natural slopes above are generally steep (30-40°). Based on an approximate landslide volume of 40 m^3, an adopted travel angle of 35° (Appendix A methodology based on data from Piha and Karekare) would project the landslide to the rear of the dwelling. Empirical methods in the GHD (2023) Muriwai risk assessment report indicate that, based on a downslope angle of approximately 35°, the predicted travel distance angle would be approximately 30° (for an unconfined travel path). This values also generally agrees with published data in Hunter & Fell (2002). This would project the landslide beyond the dwelling. A probability value of **1.0** has been adopted as a conservative approach.

3.3.2 Probability of spatial impact (LS2)

Landslide hazard LS2 involves upslope or lateral regression of the existing landslide.

- If the existing landslide hazard were to reactivate and result in regression of the headscarp, it is likely that the new landslide would follow the same path as the previous one, and hence travel towards the rear of the dwelling. As such a probability of **1.0** has been adopted for $P_{(S':H'1)}$.
- Regression of the existing landslide is expected to result in mobilisation of a somewhat smaller volume of debris. Given the observed behaviour of the previous slide (impacting the rear of the dwelling) and the topography of the site, any future failure is judged certain to almost certain to reach the dwelling. As such, a value of **0.8** is adopted for $P_{(S':H'2)}$.

3.4 Temporal spatial probability ($P_{(T:S)}$)

As discussed in Appendix A, a temporal spatial probability of **0.68** is the adopted value for each property and has been used in this assessment.

3.5 Vulnerability ($V_{(D:T)}$)

In the event a debris flow reaches the dwelling from the slopes above, the flow depth is likely to be in the order of 1.0 m. The flow is likely to have a higher volume and velocity than the previous landslide increasing the potential to result in inundation or partial collapse of the building. Given the extent of structural damage as a result of the previous landslide, a value of **0.8** is adopted for LS1.

In the event that regression of the existing landslide occurs on the slope above the dwelling, it is expected that debris would impact the rear of the dwelling but not result in building collapse. Based on the vulnerability table in Appendix A, a value of **0.1** is adopted for LS2.

3.6 Unmitigated Risk Estimation

A summary of the risk estimation for each conceivable landslide hazard is presented in Table 3.1 below. A sensitivity check assuming a higher probability of occurrence for $P_{(H)}$ is included for comparative purposes.

Table 3.1 ***Summary of unmitigated risk estimation for each hazard type by domain.***

Hazard	Annual probability of the landslide $P_{(H)} = P_{(H'1)} \times P_{(H'2)}$	Spatial probability $P_{(S:H)} = P_{S':H'1)} \times P_{(S':H'2)}$	Temporal probability $P_{(T:S)}$	Vulnerability $V_{(D:T)}$	Risk $R_{(LOL)}$	Risk evaluation*
LS1 ***(most likely future landslide hazard)***	**0.01 x 0.1**	**1.0 x 1.0**	**0.68**	**0.8**	**5.4 x 10^{-4}**	**Not tolerable**
LS1 *Sensitivity check*	*0.02 x 0.1*	*1.0 x 1.0*	*0.68*	*0.8*	*1.1 x 10^{-3}*	*Not tolerable*
LS2 ***(regression of existing landslide hazard)***	**0.1 x 1.0**	**1.0 x 1.0**	**0.68**	**0.1**	**6.8 x 10^{-3}**	**Not tolerable**
LS2 *Sensitivity check*	*0.2 x 1.0*	*1.0 x 1.0*	*0.68*	*0.1*	*1.4 x 10^{-2}*	*Not tolerable*

**The evaluation is a guide only based on recommendations from AGS (2007) which provides a suggested tolerable Loss of Life Risk for the person most at risk.*

We acknowledge that assessing risk has an inherent degree of uncertainty and may only be accurate to within half an order of magnitude. This level of uncertainty would not change the outcome of the analysis. Refer to Appendix for further discussion.

4. Conclusion and recommendation

This report has presented the results of a quantitative risk assessment for unmitigated loss of life in relation the property located at 85 Domain Crescent, Muriwai, Waitākere. Two landslide hazards (LS1 and LS2) have formed the basis of this assessment.

Assessment of the most likely future landslide (LS1) estimates the annual risk to loss of life for the person most at risk to be approximately **5.4 x 10^{-4}**. This risk is higher than the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (see Appendix A).

Assessment of the failure of the existing landslide hazard (LS2) estimates the annual risk to loss of life for the person most at risk to be approximately **6.8 x 10^{-3}**. This risk is significantly higher than the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (see Appendix A).

Potential remedial measures to lower the risk level from the existing landslide hazard (LS2) may be possible. However, identifying such measures is outside of the scope of this study.

As discussed above, this report considers geotechnical matters only. There may be other non-geotechnical considerations that affect final placard designation of which GHD are not aware, such as flood risk and structural damage to property.

We understand AC are currently reviewing their tolerable and acceptable risk criteria for risks associated with landsliding. We recommend Council review the risk assessment presented in this report against the AC risk criteria to assess whether it is appropriate to assess the property risk categorisation and remove or re-assess the current placard designation for the site.

5. Limitations

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.

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, 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 assumptions made by GHD described in this report (refer section 1.2 of this report). GHD disclaims liability arising from any of these assumptions being incorrect.

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.

This risk assessment does not mean that there will be no further landsliding impacting this property or group of properties.

Appendix A

AGS (2007) Background

1. Overview

This appendix document outlines the methods and procedures used to estimate risks to loss of life for the person-most-at-risk at the site described in the covering report. This document should be read in conjunction with the covering report as it contains information not presented in the covering report. This document should not be separated from the main report.

2. Landslide Risk Management Framework

2.1 Background

The 1998 Thredbo landslide, in which 18 persons were killed, highlighted the challenges faced from building upon steep slopes and led to the development of the Australian Geomechanics Society Landslide Risk Management guidelines, published in 2007 and now commonly referred to as AGS (2007). The suite of guidelines is recognised nationally (Australia) and internationally as world-leading practice. The reader of this report is encouraged to consult the freely available LRM resources which can be accessed at: https://landsliderisk.org/.

The "Practice Note Guidelines for Landslide Risk Management" (AGS 2007c), provide technical guidance in relation to the processes and tasks undertaken by geotechnical practitioners who prepare LRM reports including appropriate methods and techniques. The Practice Note is a statement of what constitutes good practice by a competent practitioner for LRM, including defensible and up to date methodologies and provides guidance on the quality of assessment and reporting, including the outcomes to be achieved and how they are to be achieved.

The framework for landslide risk management is presented in the figure below and represents a framework widely used internationally.

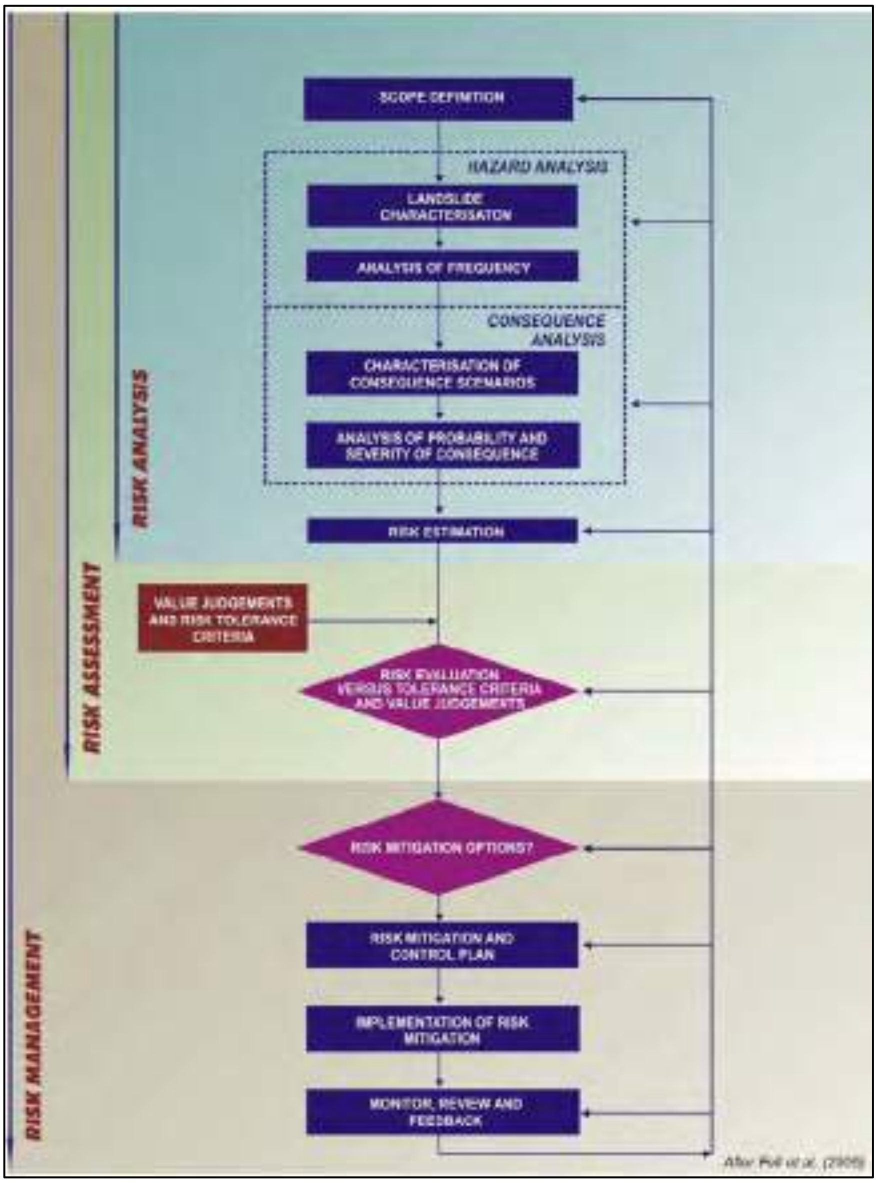


Figure A1 Framework for landslide risk management.

2.2 Risk Estimation Methodology

AGS (2007c) requires risks to loss of life to be estimated quantitatively for the person-most-at-risk. The person-most-at-risk will often but not always be the person with the greatest spatial temporal probability (i.e. the person most exposed to the risk). The Individual Risk-to-Life is defined as the risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide; or who follows a particular pattern of life that might subject him or her to the consequences of the landslide. The risk of 'loss-of-life' to an individual is calculated from:

$$\mathbf{R}_{(LoL)} = \mathbf{P}_{(H)} \times \mathbf{P}_{(S:H)} \times \mathbf{P}_{(T:S)} \times \mathbf{V}_{(D:T)}$$

Where:

$\mathbf{R}_{(LoL)}$ is the risk (annual probability of death of an individual).

$\mathbf{P}_{(H)}$ is the annual probability of the landslide (event).

$\mathbf{P}_{(S:H)}$ is the probability of spatial impact of the event impacting an individual taking into account the travel distance and travel direction given the event. For example, the probability of an individual in a building or in the open being impacted by a rockfall / landslide at a given location.

$P_{(T:S)}$ is the temporal spatial probability (e.g. of the building or location being occupied by the individual at the time of impact) given the spatial impact and allowing for the possibility of evacuation given there is warning of the event occurrence.

$V_{(D:T)}$ is the vulnerability of the individual (probability of loss of life of the individual given the impact).

2.3 Landslide Risk Assessment Uncertainty

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. By its very nature, much of the data, including historical and current inventories may be incomplete whilst an understanding of the triggering events has a degree of uncertainty attached to it. Judgement is required to estimate the nature and size of potential hazards, their frequency of occurrence and their impact on a variety of elements at risk. As these judgements are based on the knowledge, experience and understanding of the assessor, it is not unusual for different assessors to make different judgements about the level of risk.

The thought process used in establishing likelihoods, consequences and determining spatial and temporal factors for properties has been documented for transparency. The structure of the risk assessment process is well defined and values for some input parameters have been tabulated to guide standard approaches by different assessors. However, this should not be mistaken for precision given the limitations of the inputs outlined above. Generally, the levels of likelihoods and risks should be thought of as being within a range of typically +/- half an order of magnitude.

While the basis for the judgements contained in this report are well documented, and the levels of risk considered to be good representations of reality, the accuracy and precision of the process should not be overestimated and should always be used in an appropriate manner in combination with risk management including mitigation and treatment options.

3. Hazard Characterisation

AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This is generally a predictive exercise based on knowledge and understanding of the geological and geomorphological setting with a view to assembling historical evidence for past hazard events.

3.1 Defining the Most Likely Significant Landslide

Following Cyclone Gabrielle, small landslides within the Muriwai area were often noted to be shallow translational slides developed in the upper residual profile of the Awhitu Sand Formation which, under saturation, transition into debris flows. Detailed analysis by GHD of the mapped landslides within the Karekare and Piha areas, which included size, estimated volume, travel distance and travel angle, was undertaken to characterise the nature and distribution of landslides following the rainfall events that occurred in early 2023, particularly the Cyclone Gabrielle rainfall event, has been used as a basis for defining the magnitude of the ‘most significant landslide’ for the site.

A total of 80 landslides were mapped throughout Karekare and Piha following the storm events in Jan and Feb 2023. These landslides were then grouped into categories of volume in 50 m^3 increments. Results for an assessment of “frequency as categorised by volume” is shown in Figure 1 below.

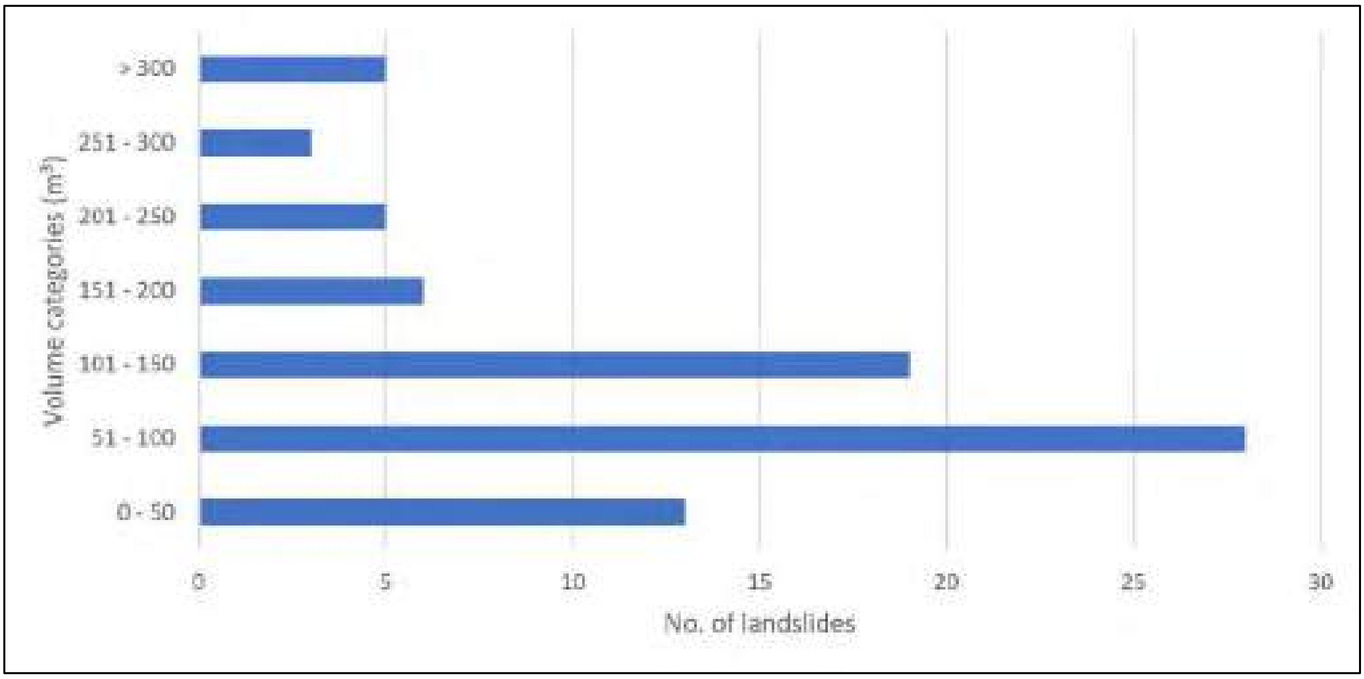


Figure A2 ***The number or frequency of mapped debris flows (on the x axis) as categorised by volume increments for mapped source areas of debris flows (on the y axis in m^3) in Karekare and Piha.***

In addition, detailed information regarding volume size, travel angle, travel distance, confinement (either unconfined or channelized) and the degree of damage caused by slides impacting dwellings and building was also collated and a number of additional graphs were developed as below:

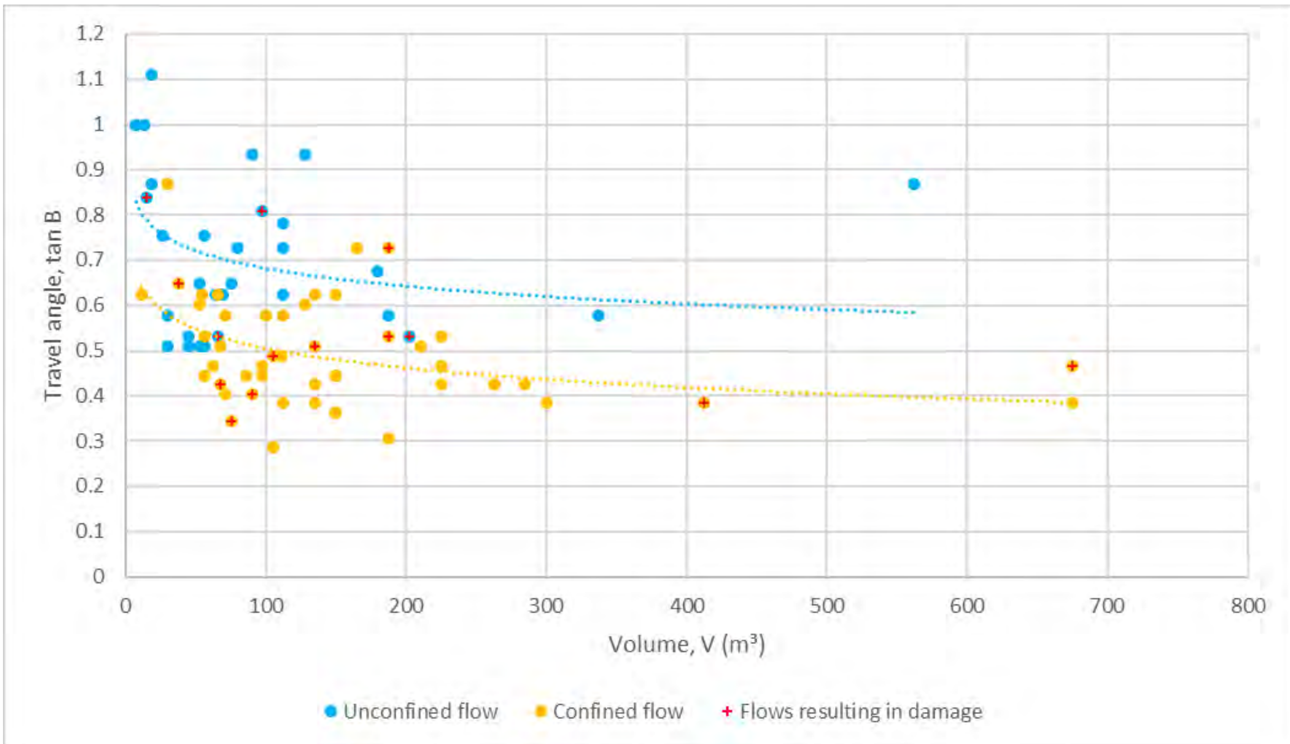


Figure A3 ***Travel angle vs volume of source area for the Karekare and Piha debris flows***

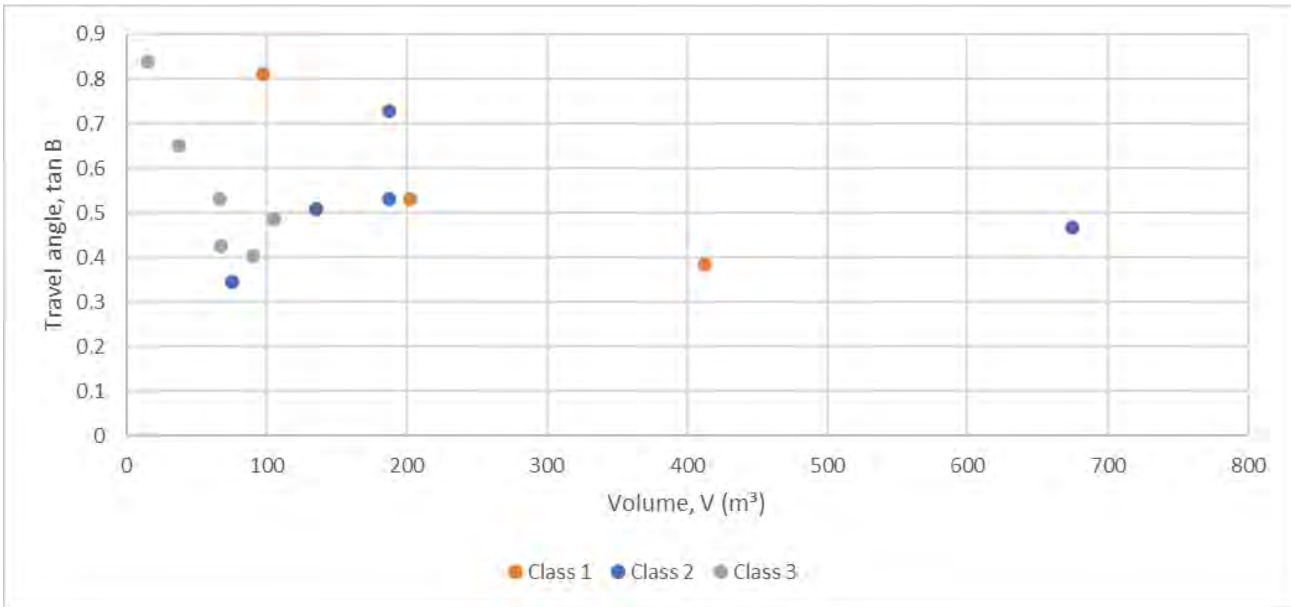


Figure A4 ***Plot of only those debris flows known to have caused some degree of damage to dwellings and buildings. Note Class 1 = Complete destruction/collapse of building, Class 2 = Partial destruction/collapse of building, significant inundation and Class 3 = Limited damage to building but no collapse or inundation, damage is other property infrastructure e.g., access stairs.***

This assessment highlights a number of important points relating the nature of these hazards including:

– Whilst a range of volumes of source areas for debris flow was noted, the most common or likely sized event was of the order of 50-100 m^3 as determined by the frequency plot.

– Many smaller volume source areas for debris flows (less than 75 m^3) typically only caused some lesser damage to buildings but once the volume increased above 100 m^3, then the vast majority of debris flows were noted to have caused partial or full collapse of dwellings and buildings.

– The greater the volume of the source area, the lower the travel angle and the greater the runout or travel distance.

– Unconfined debris flows generally have a higher travel angle compared to confined or channelized debris flows of the same volume. This means that confined or channelised debris flows have a longer runout or travel distance and hence have more potential to impact elements at risk further down the slope.

Based on this site-specific data and analysis, GHD has adopted a working definition for these risk assessments of what is termed the **most likely significant landslide** as follows:

– The volume of most likely significant landslides is assumed to be 100 $m^{3.}$

– This volume has been shown to cause significant building damage resulting in partial to full dwelling and building collapse.

– As a result, this hazard is considered to have a high probability for causing loss of life.

– Where this hazard is unconfined, the adopted travel angle based on Figure 3 has been taken as Tan (B) = 0.69 or approx. = 35°

– Where this hazard is confined or channelised the adopted travel angle based on Figure 3 has been taken as Tan (B) = 0.50 or approx. = 26.5°

– Comparison with Figure 6 from Hunter and Fell (2002) suggests the site derived travel angles are generally consistent with other data presented in that plot.

The definition of the **most likely significant landslide** is considered to be a reasonably conservative but not overly cautious estimate of the potential hazard that may affect the site. This is based on an assessment of an overview of landslides that GHD has observed in Muriwai, Karekare and Piha in 2023.

It is noted however that in some specific circumstances, larger recent debris flows may have occurred in close proximity to the site under investigation. As such, where there is evidence for a larger hazard, the assessor may

choose to adopt a larger volume event based on judgement and knowledge of that particular site. In this case other values for travel angle can be read from Figure 3.

IMPORTANT NOTE: It is duly acknowledged that volume alone does not necessarily account for the full potential of a debris flow to cause significant damage and other factors such as the degree of channelization, the additional entrainment of volume within a channel, the degree of saturation of the debris materials, the location of the source area on the hillslope, the direction of travel, the distance of travel and the velocity of the hazard at the point of impact all play important roles in the destructive capacity of any debris flow. Some of these factors are considered within the risk assessment process as conditional probabilities in spatial considerations.

3.2 Description of Other Landslide Types

As discussed in the scope of the covering report, other landslide hazards may exist at the site under assessment. These may include existing geohazards that have resulted from recent failures with the potential to pose risk to life in the immediate short-term (i.e. within the next few years) such as regression of translational failures to occur downslope of dwelling, failure of over-steepened fill and cut slopes, rockfall hazards associated with exposed rock faces/headscarps and/or loose debris remaining upslope of dwellings.

In addition, other possible geotechnical slope instability hazards relating to modified slopes (i.e. human made) may also exist and have potential to pose a risk to life - such as failures of fills, cuttings and failed retaining walls. This represents hazards that may have a range of likelihood from almost certain to possible.

Where appropriate, descriptions and definitions for each of these hazards are provided in the covering report on a case-by-case basis and will be specific to the observed hazard and actual conditions at this site.

3.3 General Descriptors for Size Classification of Landslides.

Generalized or relative descriptions of size classification systems for landslides vary significantly depending on the country of origin and the nature of the landslide hazards typically encountered. For the purposes of these assessments, GHD proposes to use the following size classification descriptions adopted from the Transport for New South Wales (TfNSW) Guide to Slope Risk Analysis Version 4 (TfNSW 2014) (see Table 3.1 below).

Table A3.1 Landslide size classification

Relative size term	Volume range	Typical mid-range dimensions (width x length x depth in metres)
Very small	<20 m3	4 x 4 x 0.5
Small	20 to 200 m3	10 x 10 x1
Medium	200 to 2000 m3	20 x 20 x 2.5
Large	2000 to 20000 m3	40 x 40 x 5
Very large	>20,000 m3	60 x 60 x 8

4. Likelihood $P_{(H)}$

Likelihood or annual probability of occurrence of the landslide, $P_{(H)}$, is one of the most critical but difficult to estimate factors as part of the risk assessment process.

4.1 The Most Likely Significant Landslide

The recent flood / storm events, the estimation of recurrence intervals for that event and the occurrence of the observed hazards form the basis for the current estimated probability of occurrence for the most likely significant landslide hazard. However, observations of the recent events noted that not all similar slopes failed as a result of

the initiating storm event and as such, an additional consideration for probability of occurrence has been included within the analysis by using conditional probabilities as follows:

$$P_{(H)} = P_{(H'1)} \times P_{(H'2)}$$

Where:

$P_{(H'1)}$ = Probability that the rainfall threshold for the most credible significant landslide is exceeded which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or 0.01 (see analysis and discussion by Auckland Council below) or 1 in 50 or 0.02 under the influence of future climate change.

$P_{(H'2)}$ =Probability that the slope for the specific assessment fails, which relates to how many of the actual slopes failed out of the total number of all slopes present. This probability is typically based a on spatial analysis of the total area of failed landslides slopes compared to the total area of all slopes for the geomorphic setting in which the site is located.

4.2 Auckland Council Guidance on Frequency for Most Likely Significant Landslide

Council provided GHD with an assessment of available rainfall data associated with Cyclone Gabrielle (Auckland Council 2023) (AC memo). During Cyclone Gabrielle, the tipping bucket rain gauge at Muriwai failed and was inundated by flood waters. The AC memo also provided rainfall analysis using AC's Quantitative Precipitation Estimate (QPE) Rain Radar System, which is a real-time rainfall product that utilises the MetService radar. The rainfall data presented by AC indicates a peak rainfall total for Muriwai during the event of 146.9mm, 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 as a result of the relatively short statistical rainfall records available in New Zealand. For the other durations modelled, the rainfall was below the 100-year event.

The AC memo recommended that an envelope of "risk" is estimated as the ARI figures will change over time and as these events are incorporated into the statistical record. The AC memo states that in general, it is considered reasonable to consider the Cyclone Gabrielle event to be in the range of 100-250 year ARI. For this assessment we have assumed that the annual likelihood of a landslide event occurring that is similar in magnitude to the February 2023 event, is about 1 in 100 (i.e., 0.01). This is considered to have a *likely* probability of occurrence.

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 are difficult to quantify.

The AC memo further recommended that risk assessment reports consider the potential for climate change to increase the frequency of high intensity rainfall. We understand that the National Institute of Water and Atmospheric Research (NIWA) has projected a 20% increase in rainfall intensity over the next 100 years which suggests that a 250-year ARI event could increase to a 50-year ARI event. Consequently, we have also included a sensitivity check based on a 50-year ARI event.

We draw the reader's attention to Section 3 of this report and reiterate that AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This report has conformed to this requirement and assessed landslide hazards that were observable during the site mapping and/or able to be interpreted via other means such as readily available aerial photographs, lidar data etc. It should be recognised that specific hazards such as rockfalls, failed retaining walls, over-steepened cuts/fill batters may have likelihoods in the *Certain to Almost Certain* range and are more likely to occur in the short term.

4.3 Other Landslide Hazards

Where other slope failures and instabilities as described in Section 3.2 are considered, individual assessments of $P_{(H)}$, the probability of occurrence, are made on the basis of expert judgment, performance of similar landslides in the area and recent site observations.

When considering hazards that may pose immediate or short-term risks to life it is probable that such hazards will have high likelihoods of occurrence that could be triggered by relatively frequent events. As a result, such hazard may have likelihoods in the *Certain to Almost Certain* range as per the ASGS2007 qualitative descriptors for likelihood.

5. Probability of Spatial Impact $P_{(S:H)}$

The AGS definition of spatial probability is represented by single term $P_{(S:H)}$ and is described as the probability of spatial impact by the landslide on the element at risk, given the landslide occurs and taking into account the travel distance and travel direction.

5.1 The Most Likely Significant Landslide - Upslope of Site

A number of conditional factors may be involved in the spatial distribution for the most likely significant landslide, and for further transparency, the following methodology has been adopted:

$$P_{(S:H)} = P_{(S':H'1)} \times P_{(S':H'2)}$$

Where:

– $P_{(S':H'1)}$ = The probability that if the landslide occurs it travels in the direction of the site under assessment. If the slopes above are consistent, and planar then probability is assumed to be 0.8 to 1.0 depending on the topography; if the originating landslide enters a channel that is directed onto the property then probability is assumed to be 1.0, or if the landslide enters a channel that is directed away from the sites then the probability is assumed to be 0.05 taking account of a small probability that the landslide may super elevate and leave the channel.

– $P_{(S':H'2)}$ = The Probability that if the landslide occurs it will travel to at least the site under assessment and will impact the property. This is to be based on two considerations as follows:

1. Modelled Behaviour based on travel distance analysis undertaken by GHD for 80 observed landslides slides in the Karekare and Piha areas (see Figure A3). Either probability = 1.0 if the travel angle projects past the dwelling, = 0.5 if the travel angle projects to the rear of the dwelling or = 0.0 if the travel angle falls short of the dwelling.

And/or

2. Observational behaviour: based on site observations of whether the previous landslides within close proximity to the study site, travelled sufficient distance to reach the site under assessment; if yes Probability = 1.0, if no, then probability = 0

– NOTE 1: The GHD analysis of travel distance highlights the effect of channelisation which shows confined debris flows travel further (i.e., they have a lower travel angle) than those which are unconfined on consistent or planar slopes. Such considerations are included on a site-by-site basis. Interestingly, this event-specific analysis also generally agrees with findings presented in Hunter and Fell (2002).

– NOTE 2: Where significant debris flows have occurred in close proximity to the site under assessment, and the observed travel distance is greater than that estimated using the modelled approach, the preferred GHD approach is to use the greater of the two travel distances to assess spatial impact.

5.2 The Most Likely Significant Landslide – Under the Dwelling/Building and/or Downslope Below the Dwelling/Building

Based on the possible failure area:

- If the failure area is > ~5 m from the dwelling then the value for $P_{(S:H)}$ will be 0 as a landslide occurring at that location will not impact dwelling. (The general assumption is that the landslide headscarp would have a length of 5m based on size of most likely significant landslide).
- If the failure area is within ~5m from the dwelling (like above) then the value for $P_{(S:H)}$ will be 0.5 to account for uncertainty of it encroaching within the footprint of the dwelling.
- If the failure area encompasses a significant portion of the dwelling then the value for $P_{(S:H)}$ will be 1.0 as there is a certain probability it will impact the dwelling.

Estimates of how far back the most significant landslide will regress are difficult to model without a detailed slope stability analysis and sufficiently accurate soil and rock inputs. This would require an intrusive geotechnical investigation which is outside the scope of this study.

GHD has adopted a more empirical approach that assesses the spatial extent of lateral downslope movement of the most likely significant landslide based on direct observations of existing landslides in close proximity to the site under assessment. In the absence of other information, a similar extent of regression has been applied to any future slides. An estimate of $P_{(S:H)}$ can then be made as to the potential interaction with the element at risk.

5.3 Other landslides – Upslope of the study site

Other types of potential landslides situated above dwellings and buildings on the site under assessment, should be assessed in a similar manner to the most likely significant landslide. Estimates of travel distance are taken from Hunter and Fell (2002) and/or previous local knowledge and/or observation of similar landslides in the area.

When undertaking short term assessments, hazards involving reactivation of existing landslides that are located upslope of the study site that didn't previously reach the site must be taken account. In addition, remobilisation of debris from any upslope landslides must also be assessed for their potential of runout or travel distance using Hunter and Fell (2002).

Similarly potential failures of modified slopes such as cuttings or fills located above or directly adjacent to dwellings and buildings must also be assessed for their spatial impact and the methods of assessment follow the same approach.

5.4 Other landslides – under buildings and downslope of the building

A similar approach to that taken for other landslides upslope has been adopted. Observation of existing failures and how much lateral downslope movement can be used as a proxy for what may occur in the future under a regression type scenario.

5.5 Temporal Spatial Probability $P_{(T:H)}$

These risk assessments have not considered specific occupancy scenarios for each individual residence. We acknowledge that the occupancy of each residence could vary significantly depending on the demographics of the residents and the usage of the residence. For example, some residences may be predominantly used as holiday accommodation, occupied mainly on weekends, whereas other residences could be permanently occupied by working families.

This assessment has assumed the following occupancies:

- Residences are typically occupied for 15 hours each day during weekdays;
- On weekends, residences are occupied for about 20 hours each day;

– The percentage of time a residence is occupied is therefore about 68%.

Any further delineation of the spatial variations in occupancy (i.e. if a bedroom is at the front or the rear of the house etc) are not considered feasible or warranted within the context of the precision of this assessment.

6. Vulnerability $V_{(D:T)}$

6.1 Most likely significant Landslide

AGS (2007c) includes a table of vulnerability values for various inundation and building damage scenarios as adapted by Finlay et al (1999). It is important to note that the AGS (2007c) vulnerability table doesn't adequately cater for all the building damage scenarios GHD has observed in Muriwai, Karekare and Piha. GHD has therefore further adapted this table and combined it with information from the TfNSW Guide to Slope Risk Analysis (2014) as well as observations of damage to buildings and structures resulting from the recent landslides in Muriwai, Karekare and Piha.

The table of vulnerability values used in this assessment is presented in Table A6.1. These values have been used as a guide and expert judgement has been applied to select a value within the range of values where appropriate on a site-specific basis.

Table A6.1 Summary of Vulnerability Values adopted

Case	Range	Typical value to be used in this assessment	Comments
Person in a building that collapses under impact from debris flow	0.8 -1.0	0.9	Death is almost certain. Evacuation unlikely to occur
If building is inundated with debris and the person is buried	0.8 -1.0	0.8	Very high potential for death Evacuation unlikely to occur
If building is inundated with debris but no collapse occurs and the person is not buried	0.01 -0.1	0.1	High chance of survival Evacuation unlikely to occur
If the debris strikes the building only	0.001-0.05	0.01	Very high chance of survival
If failure occurs below the building and results in significant collapse	0.5-0.8	0.6	Moderate to high potential for death. No forewarning signs with evacuation unlikely to occur.
If failure occurs below the building and results in partial collapse	0.01 -0.1	0.05	High chance of survival. Signs of building distress should provide occupants with opportunity to take evasive action.
If failure occurs below the building and results in damage. No collapse occurs.	0.001-0.05	0.005	Very high chance of survival. Evacuation almost certain.

7. Risk Evaluation

The main objectives of risk evaluation are usually to compare the assessed risk to risk levels that are acceptable or tolerable to the community, and therefore to decide whether to accept, tolerate or treat the risks and to set

priorities for remediation. The Tolerable Risk Criteria are usually imposed by the regulator, unless agreed otherwise with the owner/client. AGS (2007d) provides discussion and gives the AGS recommendations in relation to tolerable risk for loss of life. These are summarized in the table below.

Table A7.1 AGS Suggested Tolerable loss of life individual risk.

Situation	Suggested Tolerable Loss of Life Risk for the person most at risk
Existing Slope / Existing Development	10^{-4} per annum (1E-4 pa) or 1 in 10,000 pa
New Constructed Slope / New Development / Existing Landslide	10^{-5} per annum (1E-5 pa) or 1 in 100,000 pa

It is important to distinguish between "acceptable risks" and "tolerable risks". AGS (2007c) states that tolerable risks are risks within a range that society can live with so as to secure certain benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if practicable. Acceptable risks are risks which everyone affected is prepared to accept. Acceptable risks are usually considered to be one order of magnitude lower than the Tolerable risks.

8. References

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.

Australian Geomechanics Vol 42 No 1 March 2007 Extract "Practice Note Guidelines for Landslide Risk Management 200" AGS (2007c)

P J Finlay, G R Mostyn & R Fell (1999). 'Landslides: Prediction of Travel Distance and Guidelines for Vulnerability of Persons'. Proc 8th. Australia New Zealand Conference on Geomechanics, Hobart. Australian Geomechanics Society, ISBN 1 86445 0029, Vol 1, pp.105-113.

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

New South Wales Government, Transport for New South Wales 'Guide to Slope Risk Analysis' Version 4, April 2014.

Appendix B

Glossary of Terms

DEFINITION OF TERMS

Acceptable Risk – A risk which, for the purposes of life or work, society is prepared to accept as it is with no regard to its management. Society does not generally consider expenditure in further reducing such risks justifiable.

Authority or **Council** having statutory responsibility for community activities, community safety and development approval or management of development within its defined area/region

Consequence – The outcomes or potential outcomes arising from the occurrence of a landslide expressed qualitatively or quantitatively, in terms of loss, disadvantage or gain, damage, injury or loss of life.

Creep Failure – A time-dependant deformation mechanism where constant stress is applied to a material. Creep failure can be identified by ridges the ground surface and curved tree trunks.

Dropout – A landslide feature occurring along the length of the road-side on the downslope edge. Drop outs can result in the undermining the road carriageway.

Elements at Risk – The population, buildings and engineering works, economic activities, public services utilities, infrastructure and environmental features in the area potentially affected by landslides.

Entrainment – The process of surface sediment transportation through water and mass movement.

Frequency – A measure of likelihood expressed as the number of occurrences of an event in a given time. See also Likelihood and Probability of Occurrence.

Hazard – A condition with the potential for causing an undesirable consequence. The description of landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached material, and the probability of their occurrence within a given period of time.

Individual Risk to Life – The risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide or who follows a particular pattern of life that might subject him or her to the consequences of the landslide.

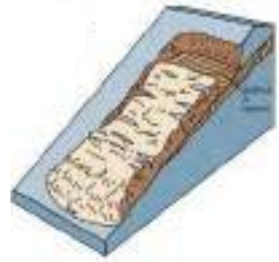
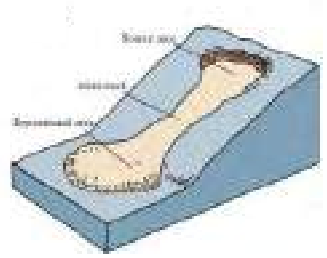
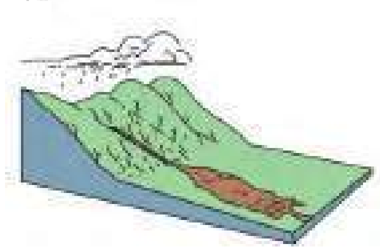
Landslide - A landslide is defined as the movement of a mass of rock, debris, or earth down a slope. The most widely used landslide classification system is that proposed by Cruden and Varnes in 1996 (after Varnes 1954 and Varnes 1978). This has been updated by Hungr, et al., 2014. In its most simple form two nouns are used to describe, firstly the type of material involved and secondly, the mechanism of failure, i.e., rock fall, debris flow.

Landslide inventory – An inventory of the location, classification, volume, activity and date of occurrence of landsliding

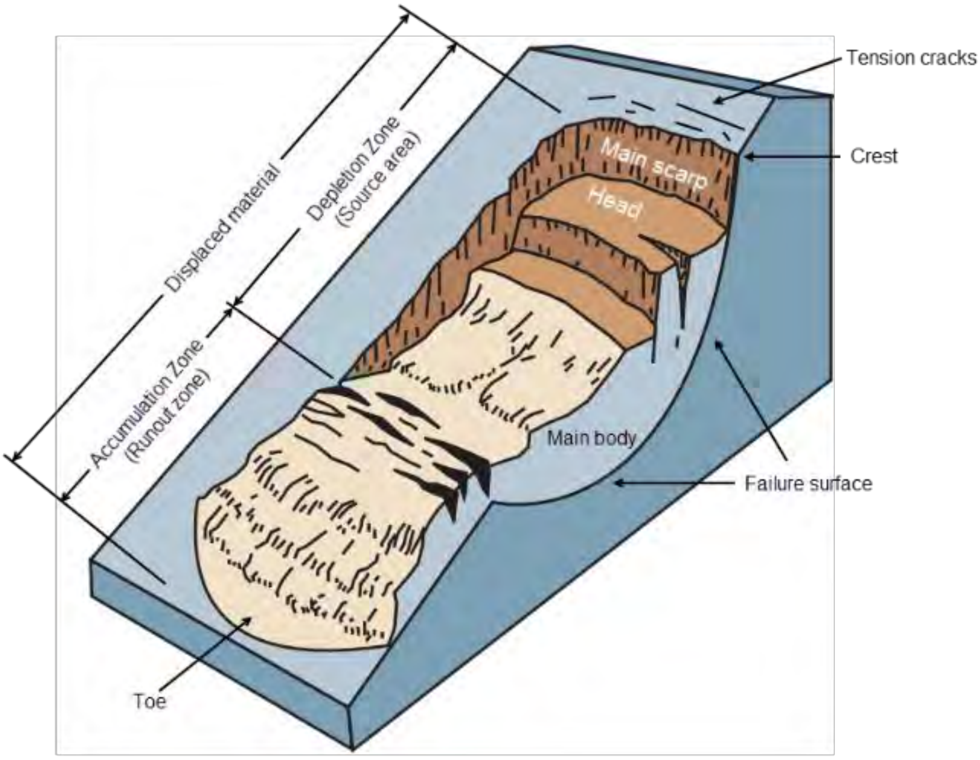
Landslide Risk - Landslide risk is defined herein as the likelihood that a particular landslide will occur and the possible consequences to a specific element at risk (property or human life) taking account of both spatial and temporal considerations.

Landslide Susceptibility – A quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding.

Landslide Classification – Referenced from Varnes, 1978.

Landslide Type	Landslide Description	Illustration
Rotational sliding	The landslide failure surface is curved concavely upward and the movement of mass is mainly rotational. Rotational movement causes back tilting of the displaced material near the headscarp.	
Translational sliding	The landslide mass moves along a planar failure surface with minor rotational movement.	
Earth flow	The movement of saturated fine-grained materials or clay bearing rocks. The displaced material forms a characteristic hourglass shape with an elongated flow path.	
Debris flow	The rapid movement of saturated, loose material caused by heavy precipitation and surface water flow. Commonly occurring on steep slopes.	
Debris avalanche	A type of debris flow that is *extremely* rapid.	
Rock fall	The separation of rocks and boulders along fractures, joints and bedding planes on steep slopes or cliffs. The movement is heavily influenced by mechanical weathering of the rock mass and gravity.	

Landslide characteristics – Modified after Varnes, 1978.



Likelihood – Used as a qualitative description of probability or frequency of the event/landslide.

Overland Flow Path – The predicated flow path of stormwater over the topography.

Permeability – The capacity of a material to allow water to pass through it. Clay materials are impermeable whereas gravels and sands are porous and therefore permeable.

Probability – A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the magnitude of the uncertain quantity or the likelihood of the occurrence of the uncertain future event. There are two main interpretations:

(i) Statistical – frequency or fraction – The outcome of a repetitive experiment of some kind like flipping coins. It also includes the idea of population variability. Such a number is called an "objective" or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment.
(ii) Subjective probability (degree of belief) – Quantified measure of belief, judgement, or confidence in the likelihood of a outcome, obtained by considering all available information honestly, fairly and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation or the quality and quantity of information. It may change over time as the state of knowledge changes.

Probability of Occurrence – used interchangeably with Likelihood.

Quantitative Risk Analysis – an analysis based on numerical values of the probability, vulnerability and consequences, and resulting in a numerical value of the risk.

Recurrence Interval (repeat period) – An estimated value of how often an event occurs based on the average time between passed events.

Regression – The continual movement of a landslide downslope and or widening/retreat of the headscarp.

The **Regulator** will be the responsible body/authority for setting Acceptable/Tolerable Risk Criteria to be adopted for the community/region/activity, which will be the basis for setting levels for Acceptable and Tolerable Risk in the application of the risk assessment guidelines.

Risk – A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by the product of probability x consequences. However, a more general interpretation of risk involves a comparison of the probability and consequences in a non-product form.

Risk Analysis – The use of available information to estimate the risk to individuals, population, property or the environment from hazards. Risk analyses generally contain the following steps: scope definition, hazard identification and risk estimation.

Risk Assessment – The process of risk analysis and risk evaluation.

Risk Control or Risk Treatment – The process of decision making for managing risk and the implementation or enforcement of risk mitigation measures and the re-evaluation of its effectiveness from time to time, using the results of risk assessment as one input.

Risk Estimation – The process used to produce a measure of the level of health, property or environmental risks being analysed. Risk estimation contains the following steps: frequency analysis, consequence analysis and their integration.

Risk Evaluation – The stage at which values and judgements enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks.

Risk Management – The complete process of risk assessment and risk control (*or risk treatment*).

Runout Distance – The horizontal distance from the source area to the distal toe.

Susceptibility – see Landslide Susceptibility

Temporal-Spatial Probability – The probability that the element at risk is in the affected area at the time of the landslide.

Tolerable Risk – A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if possible.

Transgression-regression cycles – Sedimentary deposits formed from cycles of sea level rise and fall.

Travel Angle – The angle from the crest of the source area to the distal toe of the debris (run out zone)

Vulnerability – The degree of loss to a given element or set of elements within the area affected by the landslide hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss). For property, the loss will be the value of the damage relative to the value of the property; for persons, it will be the probability that a particular life (the element at risk) will be lost, given the person(s) is affected by the landslide.

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Appendix E-3

87 Domain Crescent Landslide Risk Assessment

Waitākere Coastal Communities Landslide Risk Assessment

87 Domain Crescent, Muriwai

Auckland Council

28 March 2024

→ **The Power of Commitment**

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1. Introduction

1.1 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 turned into saturated debris flows as they travelled downslope. These flows 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 February 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).

GHD has been engaged by Auckland Council (AC)[1] to carry out landslide risk assessments and to provide associated landslide risk management advice and geotechnical investigations recommendations in the Waitakere area, specifically for the residential areas of Muriwai, Piha and Karekare. These assessments were necessary due to widespread, damaging landslides associated with Cyclone Gabrielle in February 2023. GHD has completed a landslide risk assessment[2], whereby some properties were identified as having an unacceptably high risk of being impacted by future large landslides.

1.2 Purpose of this report

The residential property at 87 Domain Crescent, Muriwai ('the site') has been assessed by GHD as having an acceptable risk from large scale landslides[3] (see the November 2023 report). However, a localised, damaging landslide has occurred near the property, and the purpose of this assessment is to carry out a Quantitative Landslide Risk Assessment (QRA) to estimate the risk of Loss of Life to individuals at the property. The outcome of the QRA will be used to inform subsequent property risk categorisation and building placard designation review by AC.

1.3 Scope

The scope of work requested by AC was as follows:

- Review available historical and recent imagery including LiDAR.
- Review pertinent historical data and GHD work undertaken as part of the wider Muriwai landslide risk assessment reported in GHD (November 2023).
- Undertake a site engineering geological assessment of landslide hazards relevant to the property.
- Undertake a QRA where landslide hazards have been identified that pose a Loss of Life landslide risk using the Australian Geomechanics Society Practice Note Guidelines for Landslide Risk Management, commonly known as AGS (2007c).
- Deliver report(s) documenting the QRA inputs and outcome.

Specifically excluded are an assessment of property risk, site specific subsurface geotechnical investigations, service inspections, and groundwater monitoring.

This assessment considers geotechnical matters only. There may be other non-geotechnical considerations that affect the final property risk categorisation or placard designation of which GHD are not aware, such as flood risk and structural damage to property.

[1] Under Contract CW198379, Master Services Agreement CCCS: CW74240 dated 7/09/2019
[2] Dated 03/11/2023, document file ref 12612462_Overall Report FINALRev0.docx
[3] In the GHD November 2023 report, 'large scale' landslide hazards refers to landslides originating from the main escarpment that typically have a volume of more than about 50 m3 with the potential to cause total or partial collapse of a dwelling.

Identification of options for the mitigation of geotechnical hazards has not been undertaken as part of this study.

Although considered unlikely, GHD reserves the right to amend the opinions, conclusions and recommendations provided within this report, should additional geotechnical information become available.

1.4 Our Approach

GHD have completed a landslide risk assessment for Muriwai that assessed the risk to life of large-scale landslide hazards to inform possible future dwelling hazard designations. The assessment was limited to 'large scale' landslide hazards originating from the main escarpment located to the south-east of Muriwai because the initial placard assessment was largely aimed at mitigating risks associated with these.

Smaller, more localised landslide hazards that could originate (or may have already initiated) from other areas in Muriwai such as within the footprint of individual residential properties were not considered in the overall risk assessment. However, these have the potential to cause damage to dwellings and subsequently pose a risk to life for residents, partly due to the relatively steep topography and the potential for high travel velocity.

The approach of identifying landslide hazards over large and common source areas, such as that used for the November 2023 Muriwai assessment, does not capture numerous, smaller scale, localised landslides. For this reason, a QRA is presented for the site based on an assessment that includes site observations and a review of the GHD (2023) report.

The QRA undertaken for this report only assesses risk to life to occupants of the dwelling due to landsliding. The assessment considers a number of hazard scenarios as follows:

1. the **most likely significant landslide hazard** based on the observed hazards with respect to the mapped landslides and their distribution within the broader landscape. In addition, considerations of the hazard relationship to topography, position on the hillslope and proximity to the elements at risk are also included. This represents a credible hazard scenario following a triggering event with a similar frequency as the February 2023 event.
2. Existing geohazards that have resulted from recent failures with the potential to pose risk to life, such as regression and/or remobilisation of translational failures that are upslope or downslope of a dwelling, or failure of oversteepened fill and cut slopes. These represent hazards that exist at the site and may be triggered by a more frequent event in the range of *certain to almost certain*[4] to occur.
3. Other possible geotechnical slope instability hazards that have the potential to pose a risk to life, such as failures of fills, cuttings and failed retaining walls. These represent hazards that may have a range of likelihood from *almost certain to possible*.

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. The methodology used for the QRA is outlined in Appendix A. The site-specific input parameters and uncertainties are described in Section 3.

A glossary of terminology is presented in Appendix B.

[4] The terminology used when referencing probabilities has been adopted from the Qualitative Measures of Likelihood table for assessing risk to property in AGS (2007c). For this assessment, these terms and associated probabilities are Certain = 0.99, Almost Certain = 0.1, Likely = 0.01, Possible = 0.001, Unlikely = 0.0001, Very Unlikely = >0.00001

2. Site conditions

2.1 Site description

The site is located at 87 Domain Crescent, Muriwai, legally described as Lot 63 DP 39644 and it has an approximate area of 827 m^2. As shown in Figure 2.1, the property is located on Domain Crescent on the lower portion of the approximately 80 m high main escarpment that is aligned to the northeast and separates the township between lower-lying plateaus to the west (near sea level), and higher areas to the south and east. Locally, the escarpment extends from Domain Crescent at its base (at an elevation of approximately 60 m RL), to Oaia Road at its crest (at an elevation of approximately 150 m RL).

There is a single dwelling on the property located towards the base of the slope, adjacent to Domain Crescent. The dwelling is constructed on timber poles built into the slope which has been modified slightly to accommodate it. The natural, vegetated slope behind the dwelling (Figure 2.1 and Figure 2.2) has an average slope gradient of approximately 35° which increases to approximately 60° where it meets a prominent north-trending ridgeline at the eastern extent of the property boundary.

Two ‘large’ landslides originating at an elevation of approximately 110 m above the site occurred during Cyclone Gabrielle but did not affect the dwelling. A third, smaller scale, localised failure originating within the neighbouring property (No. 85) that partly encroaches within the property boundary of No.87 (mapped on Figure 2.3) at approx. 83 m RL developed into a debris flow which travelled in a southwest direction impacting the rear of the neighbours dwelling (No. 85) causing structural damage.

Two overland flow paths are mapped from Auckland Council’s GeoMaps to the north and south of the property boundary (Figure 2.3) originating at approximately 105 m RL and 75 m RL to the southeast of the dwelling. Both overland flow paths have a catchment size of approximately 2000 m^2 to 4000 m^2. The travel paths of the debris associated with the two large scale landslides above the site, to the north and south, appear to correlate with the mapped overland flow paths. No overland flow paths are mapped on the slopes within the property boundary.

Figure 2.1 Steep vegetated slope at the rear of the dwelling

Figure 2.2 Steep vegetated slope at the rear of the dwelling

Figure 2.3 Site location along Domain Crescent

2.2 Published geology

The published 1:50,000 scale geological map of the area (Hayward, 1983) indicates the site is entirely underlain by the Awhitu Sand Formation (mp), part of the Kaihu Group (Figure 2.4).

Awhitu Sands (‘qs’) are Pliocene aged (less than 2 Mya) characterised as ‘coarse sand, clayey, often limonitised (as laterally discontinuous layers), with minor tuff, lignite and siltstone’ (Hayward, 1983). The formation originated as coastal sand deposits. Awhitu Sands are generally oxidised to an orange-brown colour when exposed at the surface, resulting in a weak iron-cementation that allows for the development of large, more than 50 m high steep slopes, such as the escarpment.

The formation is weakly bedded and cross-bedded at the sub metre scale. Locally the formation is inferred to dip north and eastward at a shallow angle. Occurrences of silty/clayey horizons are occasionally visible in outcrop and have been encountered within boreholes, however it is unclear how persistent they are spatially.

Although not mapped, more recent colluvium material formed as a result of ongoing erosion and periodic landsliding associated with escarpment recession is likely present on the basal/lower slopes of the escarpment.

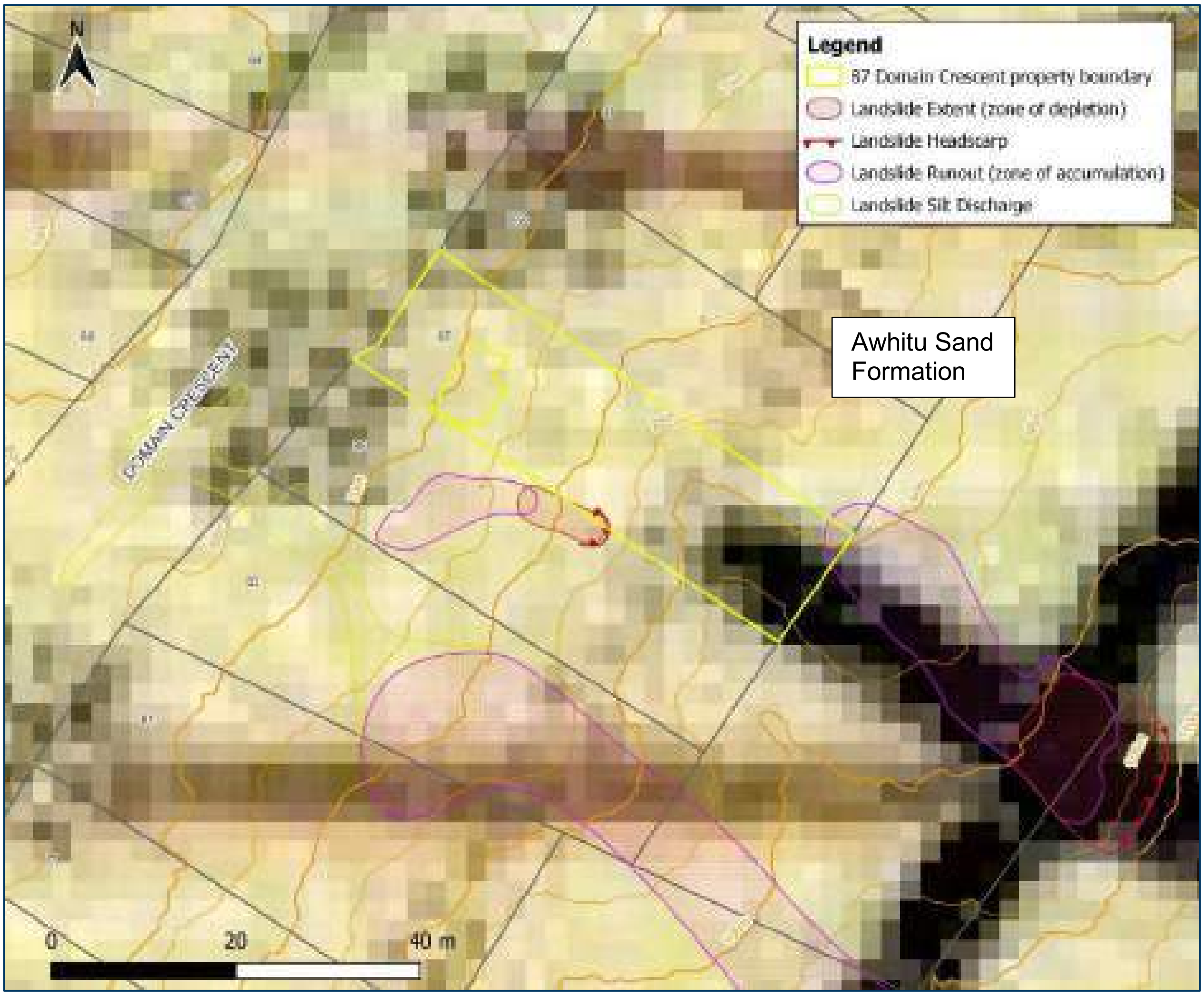


Figure 2.4 ***Excerpt of the Waitākere 1:50,000 scale geological map (Hayward, 1983[5]), illustrating the underlying geology at the site location.***

[5] Hayward, B.W. 1983: Sheet Q11, Waitakere. Geological Map of New Zealand 1:50,000 Map

2.3 Historical data summary

A summary of the historical data relevant to 87 Domain Crescent is presented in Table 2.1.

Table 2.1 Summary of historical data

	Applicable data available	Notes
Historic aerial photos	1940, 1950, 1953, 1975, 2000, 2004, 2008, 2010-2011, 2015-2017, 2022	- No obvious evidence of instability was identified from the historical aerials within the property itself. - Evidence of wider scale erosion evident from 1940, where many of the spurs leading off main escarpment are bare as well as section of the crest of the escarpment. Suggests ongoing erosion of surficial soil. No regression of escarpment observed. - Photos sourced from Retrolens and Auckland Council Geomaps.
NZ Geotechnical database	One borehole (BH-MH05, Figure 2.1) completed by GHD in August 2023. Located 30 m west of south-west corner of property boundary.	- 10.95 m deep borehole. - 0 – 5.6 m: Ancient colluvial deposits generally comprising sandy silt and silty sand. - 5.6 – 10.95 m: Awhitu sand formation comprising variably cemented sand (medium dense to very dense)
Council GeoMaps	Overland flow data from Auckland City Council ArcGIS.	- Discussed in Section 2.1.
Rapid building Assessment Geotech reporting	N/A	N/A
Independent geotechnical reports	N/A	N/A
Anecdotal information	N/A	N/A
LiDAR Imagery	Feb 2023 Digital Terrain Model.	- Headscarps in the escarpment crest suggest ongoing recession through debris flows. - Headscarps also seen on smaller ridgelines extending down the escarpment. However no clear evidence of these in the ridgeline within the property. - Possible hummocky ground on the natural slopes above the dwelling leading up to the ridgeline on 87 Domain Crescent.

2.4 Engineering geological model

2.4.1 Awhitu Sand Formation

Awhitu Sands are exposed within the entire escarpment and have generally been described as medium dense to very dense sands overlying massive, extremely weak, moderately weathered, iron-cemented fine to coarse sandstone. Irregular layers of clay and silt rich material are typically spaced every 5-10 m and relatively thin (less than 1.0 m and often less than 0.1 m). The strength profile of the Awhitu Sands displays a relatively linear increase with depth.

The in-situ nature of the Awhitu Sands suggests they are relatively permeable. However, as discussed in the November report there is also significant evidence for perched groundwater tables shown by:

- Multiple occurrences of groundwater seeps or springs emerging within the middle and base of the escarpment slope face, from above underlying (presumed aquiclude) layers of clay and silt rich beds as well as heavily oxidised iron pans
- Variable and sharply changing weathering profile with localised layers of cemented iron oxidised sand between un-oxidised material at depth.

2.4.2 General landslide characteristics

As described in the November report (GHD 2023), the landslides identified across Muriwai following the February 2023 event can be categorised into two types based on their physical characteristics as follows:

Large slips: typical headscarp widths of 30-70 m, with source and debris runout areas more than 100 m in length, often extending well past the base of the escarpment onto the flatter slopes below, and

Smaller isolated slips: generally with headscarp widths of less than 30 m and extending less than 50 m. As a result debris from these landslides generally did not reach the base of the escarpment.

2.4.3 Landslide affecting the site

The landslide that occurred above the site, within the neighbour's property, is illustrated by site mapping on Figure 2.5 and is also shown in the context of LiDAR Hillshade imagery on Figure 2.6 below. An interpretive cross section prepared through the site is presented in Figure 2.7. Ground conditions have been interpreted from a combination of historical data, site mapping and nearby geotechnical investigation data. The cross section is indicative only and may not be representative of actual conditions.

The landslide headscarp (Figure 2.8) has an approximate width of 7 m and is approximately 10 m above the rear of the dwelling, close to the crest of a ridgeline. Following a high degree of ground saturation, the landslide initiated on a 30-35° vegetated slope as a shallow (~ 0.5 m deep) translational failure (Figure 2.9) which developed into a debris flow, entraining additional material on its descent. The initial landslide source volume was approximately 20 m^3, increasing to approximately 60-80 m^3 following entrainment. The landslide impacted the rear of the neighbouring dwelling (Figure 2.10). No landslide debris entered the property of No. 87.

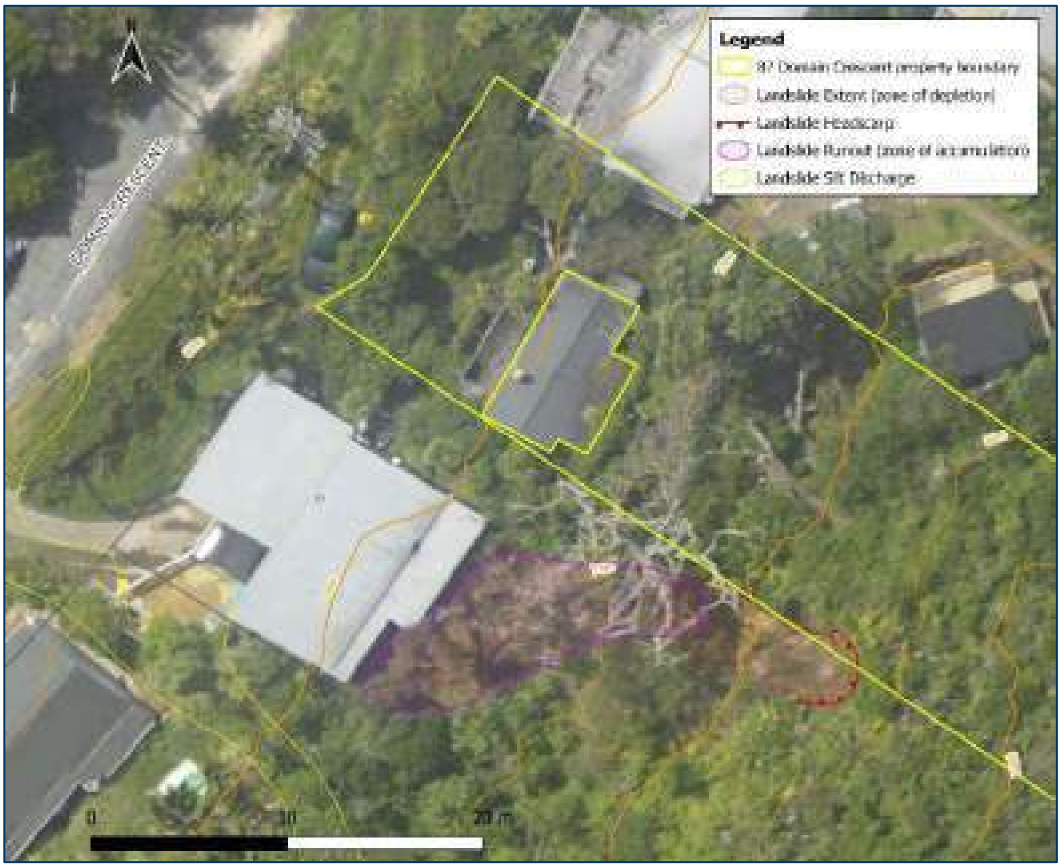


Figure 2.5 GHD site mapping of the landslide affecting the site

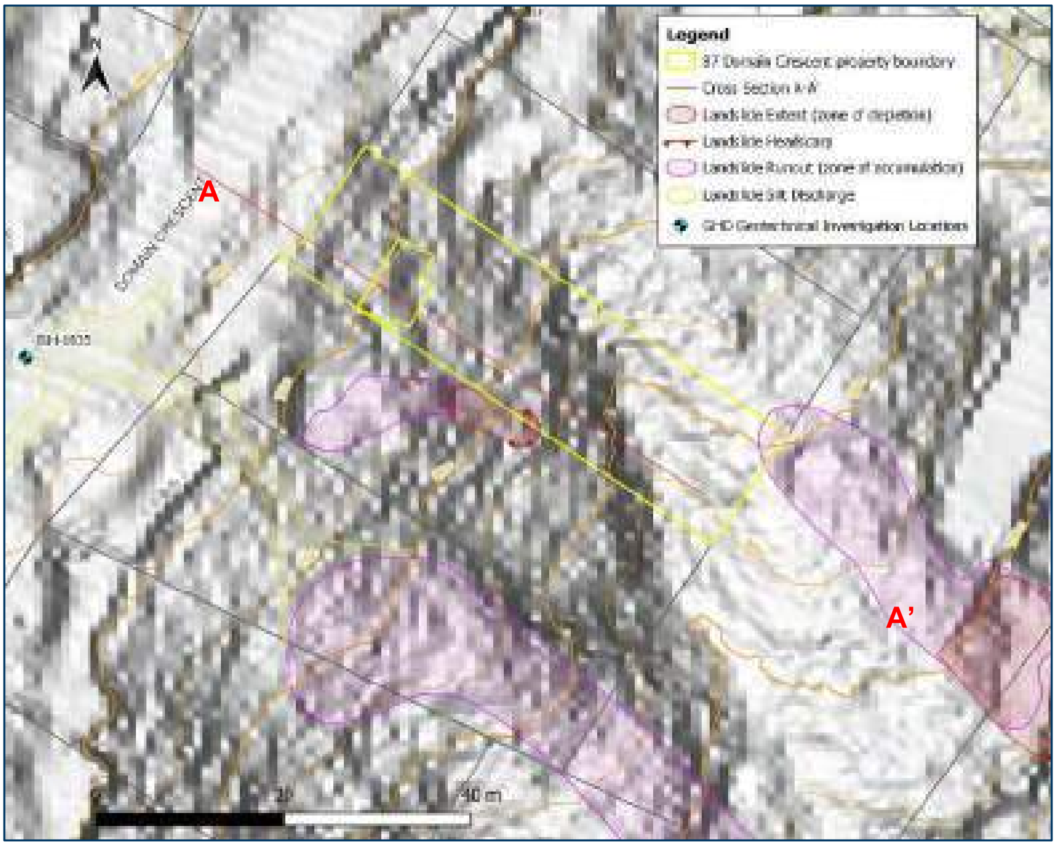


Figure 2.6 Landslide location relative to the site shown on LiDAR Hillshade (source: Auckland Council Feb 2023).

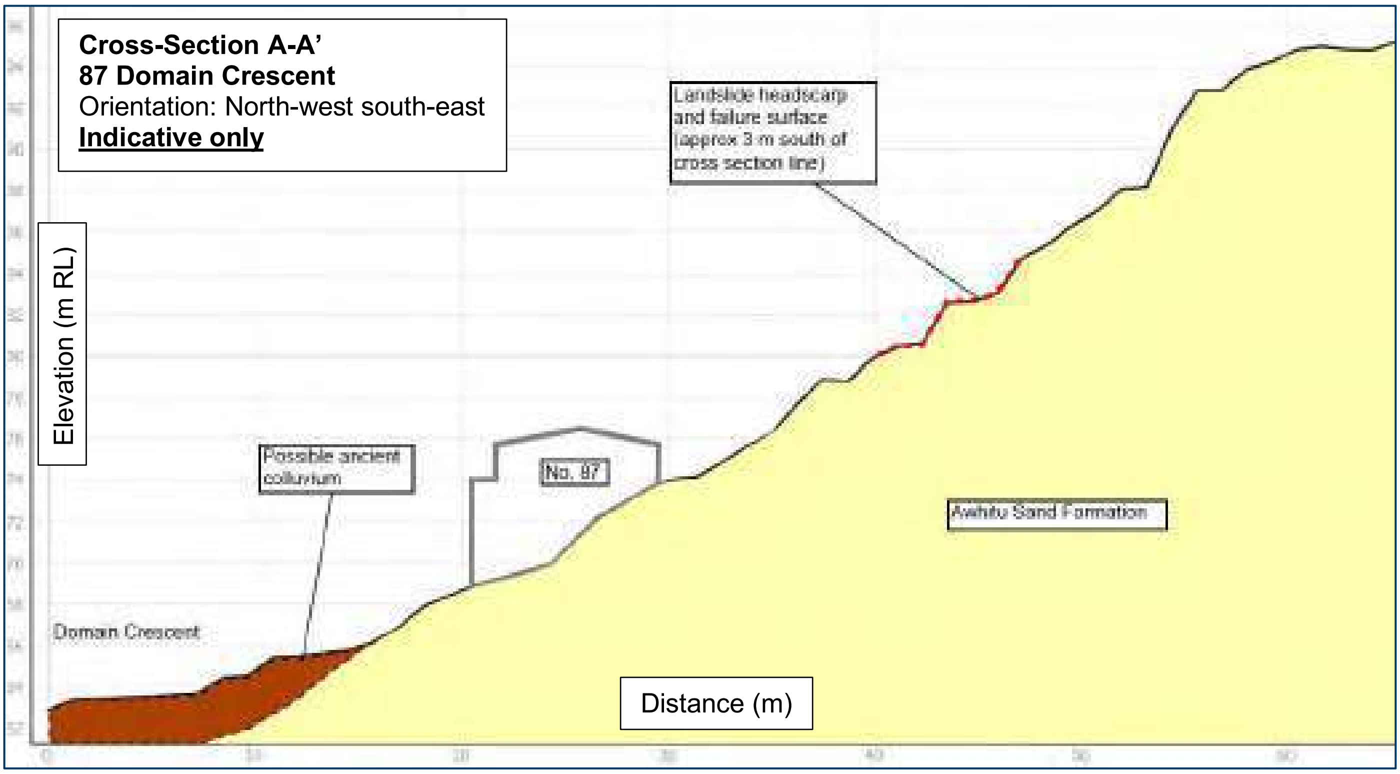


Figure 2.7 Indicative cross section A-A' through 87 Domain Crescent

Figure 2.8 Exposed headscarp of landslide.

Figure 2.9 *Failure surface (evacuated zone) exhibiting evidence of post failure erosion. Looking upslope.*

Figure 2.10 *Debris piled up at the rear of the dwelling at No. 85 Domain Crescent (estimated up to 1.5 m thick)*

3. Landslide risk estimation

The Australian Geomechanics Society Landslide Risk Management guidelines, published in 2007 and now commonly referred to as AGS (2007), have been adopted for the following unmitigated loss of life landslide risk assessment. Appendix A provides background information and guidance on how the methodology has been applied for assessing risk to life at the site.

The existing dwelling has been considered as the element at risk for this assessment. Where appropriate, sensitivity checks have been undertaken for comparative purposes.

3.1 Hazard characterisation

The landslide hazard considered as part of this assessment is as follows:

– **LS1** (Landslide Hazard 1) – The most likely future landslide to occur somewhere on the slopes above the property. The landslide would be a shallow failure with a volume in the order of 20-40 m^3 that develops into a debris flow entraining additional downslope material. The assumed landslide characteristics have been inferred from observations of the previous failure and landslides to occur elsewhere in Muriwai. The possible source area considered for a future landslide above the dwelling, highlighted on Figure 3.1 and Figure 3.2 below, is constrained by two relatively prominent ridgelines.

3.2 Likelihood of landsliding ($P_{(H)}$)

The basis for estimating probability of occurrence for the landslide hazard considered as part of this assessment is provided in Appendix A and the probabilities adopted are provided below.

3.2.1 Likelihood of LS1

Two considerations of probability for occurrence for the most likely future landslide are:

– $P_{(H'1)}$ is the probability that the rainfall threshold for the most likely significant landslide is exceeded, which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or **0.01** (see analysis by AC in Appendix A) or 1 in 50 or **0.02** under the influence of future climate change.

– $P_{(H'2)}$ is the probability that the slope above the dwellings fails. A single landslide occurred on the slopes above and near the dwelling. Considering the total area of the slope above the dwelling with similar conditions, and therefore considered susceptible to failure, an estimate of 5% failed during the February 2023 rainfall event. A value of $P_{(H'2)}$ **= 0.05** has been adopted.

3.3 Probability of spatial impact ($P_{(S:H)}$)

Our estimate of spatial probability is based on several factors which depend on the landslide hazards being considered and site-specific slope conditions. Our approach is detailed in Appendix A. Figure 3.1 and Figure 3.2 below provide an indication of the slope conditions at 87 Domain Crescent and the surrounding area (slope angles and inferred preferential flow paths, respectively).

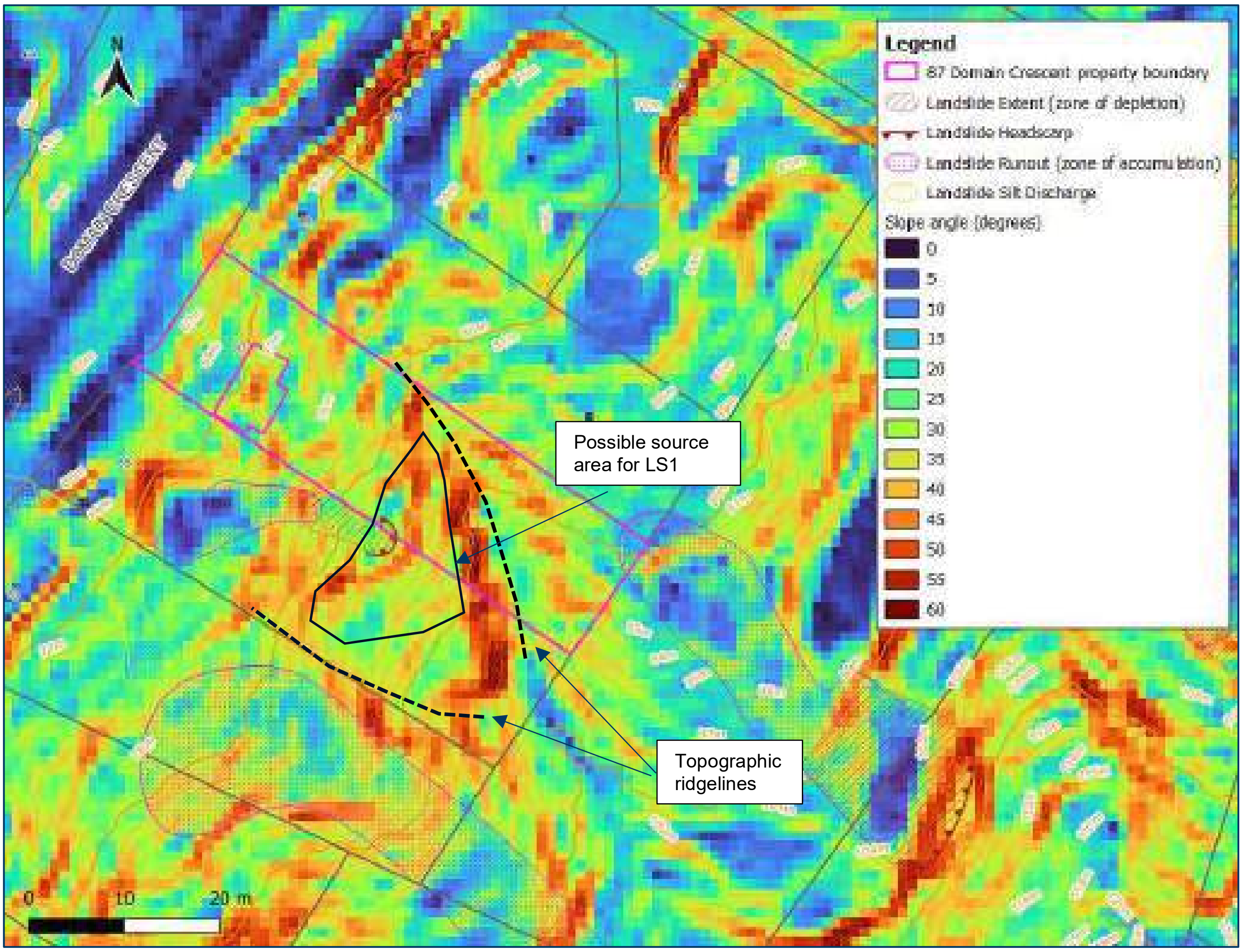


Figure 3.1 Slope map of 87 Domain Crescent and surrounding area. Slope angles based on 2023 DTM data.

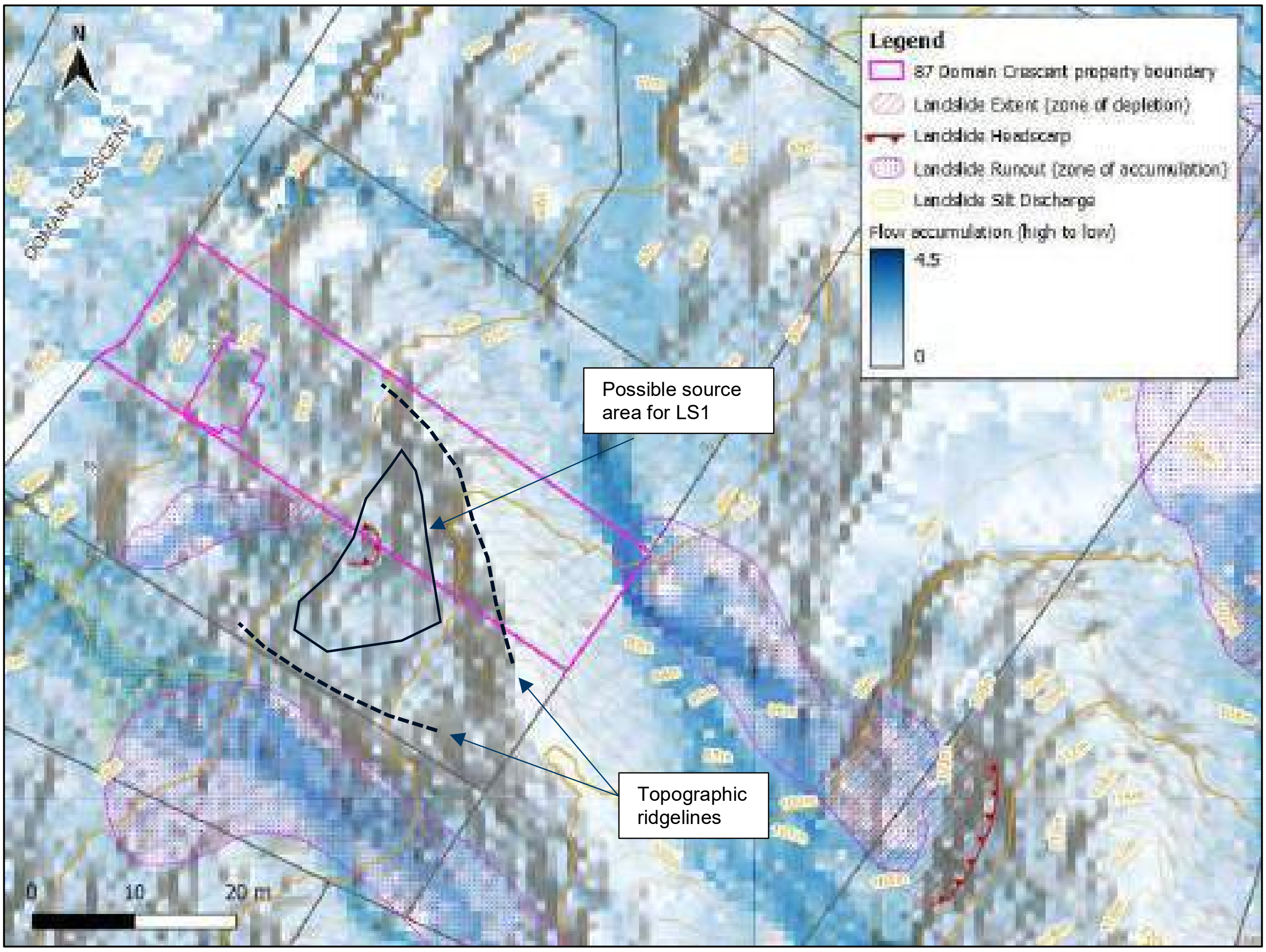


Figure 3.2 Flow accumulation map of 87 Domain Crescent and surrounding area. Indicates preferential flow path for surface water. Modelling based on 2023 DTM data.

3.3.1 Probability of spatial impact (LS1)

Two conditional factors are considered for the most likely significant landslide:

– $P_{(S':H'1)}$ is the probability that if the landslide occurs it travels in the direction of the site. Based on the position of the dwelling at the base of a relatively planar slope exhibiting a somewhat concave geomorphology at its crest, a landslide initiating in the possible source area above the site (Figure 3.1) would likely travel downslope (northwest) towards the dwelling. Based on the flow accumulation plot (Figure 3.2) and the topographic contours shown in Figure 2.3, we judge that a landslide is unlikely to take a preferential flow path which diverts it away from the dwelling. A value of **1.0** is adopted.

– $P_{(S':H'2)}$ is the probability that if the landslide occurs it will reach the dwelling. The natural slopes above are generally steep (~35°). Based on the landslide volume approach (using an approximate landslide volume of 50 m^3), a travel angle of 35° would be adopted (Appendix A methodology based on data from Piha and Karekare). This would project the landslide to the rear of the dwelling.

  Empirical methods in the GHD (2023) Muriwai risk assessment report indicate that, based on a downslope angle approach (using approximately 35°), the predicted travel distance angle would be approximately 30° (for an unconfined travel path). This value also generally agrees with published data in Hunter & Fell (2002) (approximately 32°). This would project the landslide beyond the dwelling. Therefore, a probability of impact value of **1.0** has been adopted as a conservative approach.

3.4 Temporal spatial probability ($P_{(T:S)}$)

As discussed in Appendix A, a temporal spatial probability of **0.68** is the adopted value for each property and has been used in this assessment.

3.5 Vulnerability ($V_{(D:T)}$)

In the event a debris flow reaches the dwelling from the slopes above, it is likely to be small[6] in size and have a flow depth in the order of 1.0 m. Given the landslide is likely to initiate at similar elevation to the previous landslide to occur on the neighbouring property, it is assumed it will have a similar behaviour, impacting the rear of the dwelling resulting in significant structural damage and potential collapse. A value of **0.8** is adopted for LS1.

3.6 Unmitigated Risk Estimation

A summary of the risk estimation for each conceivable landslide hazard is presented in Table 3.1 below. A sensitivity check assuming a higher probability of occurrence for $P_{(H)}$ is included for comparative purposes.

Table 3.1 Summary of unmitigated risk estimation for each hazard type by domain.

Hazard	Annual probability of the landslide $P_{(H)} = P_{(H'1)} \times P_{(H'2)}$	Spatial probability $P_{(S:H)} = P_{S':H'1)} \times P_{(S':H'2)}$	Temporal probability $P_{(T:S)}$	Vulnerability $V_{(D:T)}$	Risk $R_{(LOL)}$	Risk evaluation*
LS1 ***(most likely future landslide hazard)***	**0.01 x 0.05**	**1.0 x 1.0**	**0.68**	**0.8**	**2.7×10^{-4}**	**Not tolerable**
LS1 *Sensitivity check*	*0.02 x 0.05*	*1.0 x 1.0*	*0.68*	*0.8*	*5.4×10^{-4}*	*Not tolerable*

**The evaluation is a guide only based on recommendations from AGS (2007) which provides a suggested tolerable Loss of Life Risk for the person most at risk.*

We acknowledge that assessing risk has an inherent degree of uncertainty and may only be accurate to within half an order of magnitude. This level of uncertainty would not change the outcome of the analysis. Refer to Appendix A for further discussion.

[6] Table A3.1 Landslide size classification in Appendix A

4. Mitigation option

4.1 General

A mitigation measure has been selected that could be adopted at this site to lower the risk level associated with future landslides (LS1) occurring above the site to a tolerable level. The following section provides a high-level conceptual mitigation option for the dwelling with an estimated cost using the principles used by GHD for other properties in Muriwai[7].

Landslide hazard 1 (LS1) is considered as the hazard requiring mitigation and for the purpose of this assessment it is assumed that the landslide would occur on the slopes directly above the dwelling, have a maximum volume of approximately 40 m^3 and an estimated velocity of rapid to very rapid[8].

The selection is based on existing information and site knowledge. Some of the considerations when selecting a suitable mitigation option include:

– The slope angle and foundation conditions of the proposed barrier location. This is an important consideration for mass gravity embankment-type barriers.
– Site conditions that may enable or limit access for construction.
– The location of the property boundary, with the aim of locating the mitigation structure within this.
– The volume capacity of the proposed debris flow barrier.
– The barrier will require ongoing inspection and maintenance, which is a future liability for the owner.
– The barrier will require access to enable removal of debris.
– The locations and limitations associated with the presence of trees needs to be considered in the design and construction of barriers.
– Whether the site is within a Significant Ecological Area (SEA) where modification of the environment may trigger Resource Consent requirements.

4.2 Selected mitigation option

A flexible debris flow ‘fence type’ barrier has been selected as the most feasible option to mitigate the risk to the dwelling on the site. The limited access at the rear of the property and the steep slope conditions preclude alternative options such as a mass gravity embankment-type barrier. As shown in Figure 4.1 below, the flexible barrier comprises mesh supported by steel posts with upslope and lateral wire support ropes that are anchored several metres into the ground. An example of a commercially available proprietary system that could be adopted is a Geobrugg SL150 (3.5 m constructed height) or a modified RXI300 (5 m constructed height) or equivalent.

[7] Reported in GHD report, dated 12 October 2023 ‘Muriwai debris flow mitigation’, reference 12612462_MitigationOptionsMuriwai final draft
[8] Cruden, D., & Varnes, D. (1996). Landslide types and processes. In K. Turner & R. Schuster (Eds.), Landslides: Investigation and Mitigation (Chap. 3, pp. 36–75). Transportation Research Board: Washington.

Figure 4.1 Example of proprietary flexible debris flow barrier

Elements of the barrier system may be exchanged to accommodate specific site conditions. An example of this is where an end terminal is located close to a property boundary. Wire ropes attached to the top of the barrier end post attach to ground anchors several metres upslope and laterally. A pressure post can replace this end post to keep hardware within the property (see Figure 4.2).

The proposed barrier location is above the dwelling at an approximate elevation of 76 m RL and has an approximate length of 10 m (Figure 4.3 below).

Figure 4.2 Example of a pressure post that can be used at the end of flexible barriers that may be used at property boundaries

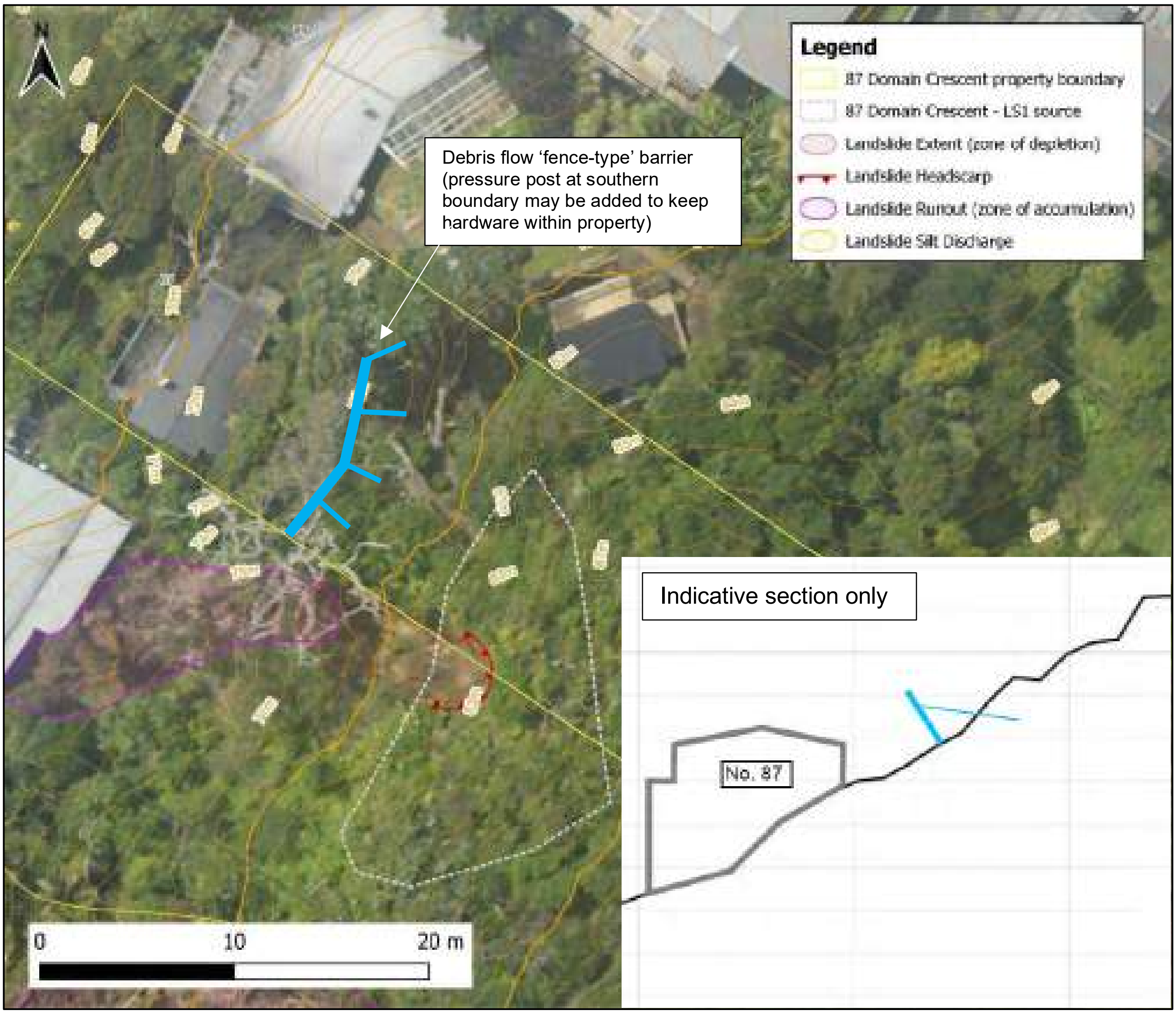


Figure 4.3 Site plan showing proposed mitigation option for 87 Domain Crescent

Some of the key site-specific factors to be considered in the design and construction of this mitigation option include:

- Part of the barrier is located outside of the property boundary (within 85 Domain Crescrent).
- Access is considered to be 'hard' as there is no clear access to the proposed barrier location, which is on a slope of approximately 35°. Enabling works are likely required.
- The property is within the Significant Ecological Area (SEA) and damage to trees/vegetation would be likely for both access and construction.
- The subsurface conditions are likely to comprise medium dense to very dense sands overlying massive, extremely weak sandstone.
- Based on an estimated volume of debris of 40 m^3, a fence type barrier height of 3.5 m would be adequate.

4.3 Mitigated loss of life risk estimation

Table 4.1 below presents the resulting risk estimation following implementation of the selected mitigation option. The mitigated risk assessment only considers the failure of the barrier and therefore the spatial probability has been reduced by two orders of magnitude (i.e to 1% probability of failure). This is to reflect the unlikely potential for the barrier to become ineffective and therefore fail to prevent the landslide from reaching the dwelling.

Table 4.1 Summary of unmitigated v mitigated loss of life risk estimation for 87 Domain Crescent

Property	Hazard	Annual probability of the landslide $P_{(H)}$	Spatial probability $P_{(S:H)}$	Temporal Spatial probability $P_{(T:S)}$	Vulnerability $V_{(D:T)}$	Unmitigated Risk (from Risk Assessment Report)	
						Risk $R_{(LOL)}$	Risk Evaluation
Unmitigated Risk	LS1	0.01 x 0.05	1.0	0.68	0.8	2.7×10^{-4}	Not tolerable
Mitigated Risk		**0.01 x 0.05**	**0.01**	**0.68**	**0.8**	$\mathbf{2.7 \times 10^{-6}}$	**Acceptable**
Unmitigated Risk	LS1 (Sensitivity case)	*0.02 x 0.05*	*1.0*	*0.68*	*0.8*	5.4×10^{-4}	*Not tolerable*
Mitigated Risk		*0.02 x 0.05*	*0.01*	*0.68*	*0.8*	5.4×10^{-6}	*Acceptable*
Values in italics represent a sensitivity check which considers a higher annual probably of occurrence.							

4.4 Mitigation costs

The cost for the proposed mitigation is a high-level estimate based on generic designs. The contingency (uncertainty) is considered high. Geobrugg have provided advice and cost estimates for a flexible debris flow barrier which have been used to inform our total estimate. Whole of life costs have also been considered (e.g. inspections, maintenance).

The total (construct and maintain) P50 expected estimate is in the order of **$215,000** ex GST. An additional cost of $35,000 ex GST for SEA consenting has also been allowed for, giving a total cost of $250,000 ex GST.

We would like to emphasize that the concept and estimated cost presented are high level and indicative only. Further design effort by others is required to better define the details and costs.

5. Conclusion and recommendation

This report has presented the results of a quantitative risk assessment for unmitigated loss of life in relation the property located at 87 Domain Crescent, Muriwai, Waitākere. One landslide hazard (LS1) has formed the basis of this assessment.

Assessment of the most likely future landslide (LS1) estimates the annual risk to loss of life for the person most at risk to be approximately **2.7×10^{-4}**. This risk is higher than the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (see Appendix A).

Detailed in Section 4, a potential remedial measure to lower the risk level associated with future failures (LS1) above the site includes a dynamic flexible fence-type landslide barrier to catch debris upslope of the existing dwelling at an indicative cost of $250,000 ex GST. An estimated mitigated annual risk to loss of life for the person most at risk is approximately 2.7×10^{-6}, which is 'tolerable' (AGS 2007c).

As discussed above, this report considers geotechnical matters only. There may be other non-geotechnical considerations that affect final placard designation of which GHD are not aware, such as flood risk and structural damage to property.

We understand AC are currently reviewing their tolerable and acceptable risk criteria for risks associated with landsliding. We recommend Council review the risk assessment presented in this report against the AC risk criteria to assess whether it is appropriate to assess the property risk categorisation and remove or re-assess the current placard designation for the site.

6. Limitations

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.

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, 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 assumptions made by GHD described in this report (refer section 1.2 of this report). GHD disclaims liability arising from any of these assumptions being incorrect.

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.

This risk assessment does not mean that there will be no further landsliding impacting this property or group of properties.

Appendix A

AGS (2007) Background

1. Overview

This appendix document outlines the methods and procedures used to estimate risks to loss of life for the person-most-at-risk at the site described in the covering report. This document should be read in conjunction with the covering report as it contains information not presented in the covering report. This document should not be separated from the main report.

2. Landslide Risk Management Framework

2.1 Background

The 1998 Thredbo landslide, in which 18 persons were killed, highlighted the challenges faced from building upon steep slopes and led to the development of the Australian Geomechanics Society Landslide Risk Management guidelines, published in 2007 and now commonly referred to as AGS (2007). The suite of guidelines is recognised nationally (Australia) and internationally as world-leading practice. The reader of this report is encouraged to consult the freely available LRM resources which can be accessed at: https://landsliderisk.org/.

The ”Practice Note Guidelines for Landslide Risk Management” (AGS 2007c), provide technical guidance in relation to the processes and tasks undertaken by geotechnical practitioners who prepare LRM reports including appropriate methods and techniques. The Practice Note is a statement of what constitutes good practice by a competent practitioner for LRM, including defensible and up to date methodologies and provides guidance on the quality of assessment and reporting, including the outcomes to be achieved and how they are to be achieved.

The framework for landslide risk management is presented in the figure below and represents a framework widely used internationally.

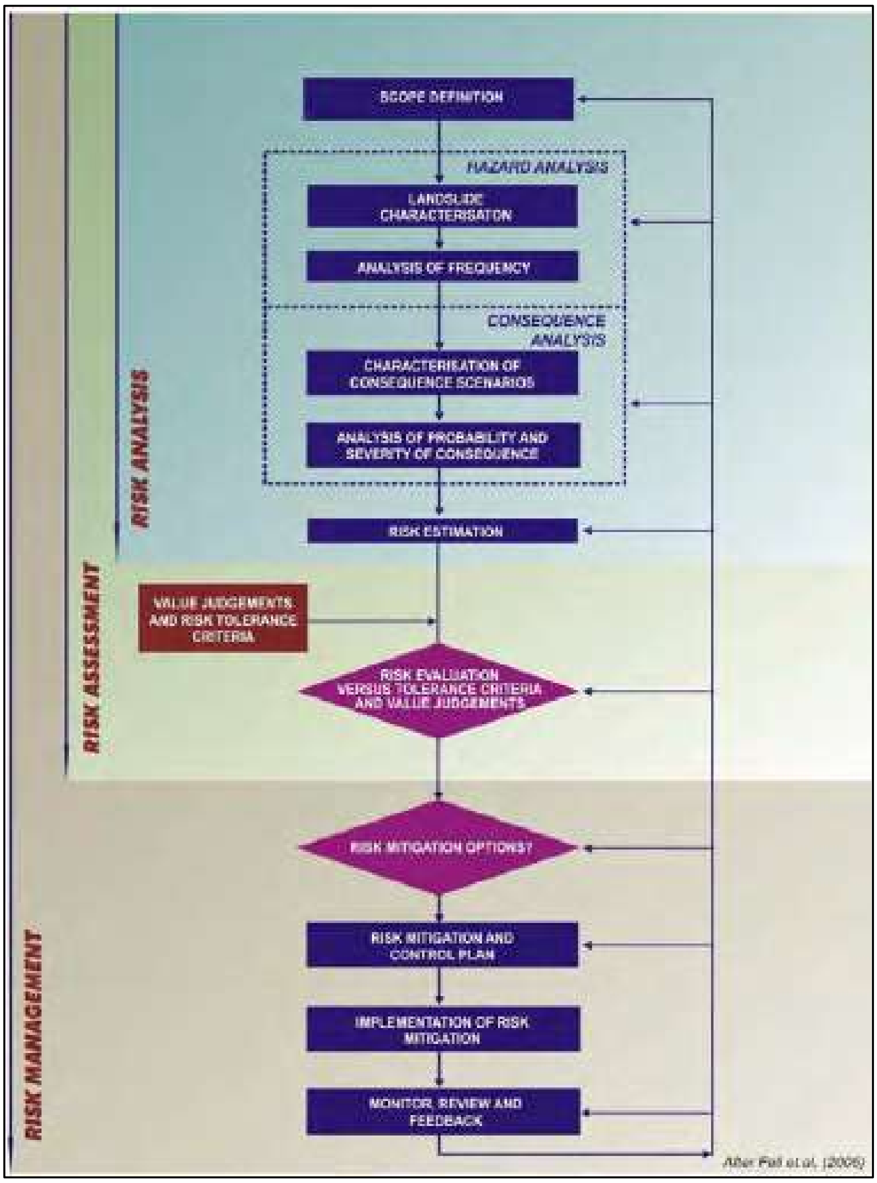


Figure A1 Framework for landslide risk management.

2.2 Risk Estimation Methodology

AGS (2007c) requires risks to loss of life to be estimated quantitatively for the person-most-at-risk. The person-most-at-risk will often but not always be the person with the greatest spatial temporal probability (i.e. the person most exposed to the risk). The Individual Risk-to-Life is defined as the risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide; or who follows a particular pattern of life that might subject him or her to the consequences of the landslide. The risk of ‘loss-of-life’ to an individual is calculated from:

$$\mathbf{R}_{(LoL)} = \mathbf{P}_{(H)} \times \mathbf{P}_{(S:H)} \times \mathbf{P}_{(T:S)} \times \mathbf{V}_{(D:T)}$$

Where:

$\mathbf{R}_{(LoL)}$ is the risk (annual probability of death of an individual).

$\mathbf{P}_{(H)}$ is the annual probability of the landslide (event).

$\mathbf{P}_{(S:H)}$ is the probability of spatial impact of the event impacting an individual taking into account the travel distance and travel direction given the event. For example, the probability of an individual in a building or in the open being impacted by a rockfall / landslide at a given location.

P$_{(T:S)}$ is the temporal spatial probability (e.g. of the building or location being occupied by the individual at the time of impact) given the spatial impact and allowing for the possibility of evacuation given there is warning of the event occurrence.

V$_{(D:T)}$ is the vulnerability of the individual (probability of loss of life of the individual given the impact).

2.3 Landslide Risk Assessment Uncertainty

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. By its very nature, much of the data, including historical and current inventories may be incomplete whilst an understanding of the triggering events has a degree of uncertainty attached to it. Judgement is required to estimate the nature and size of potential hazards, their frequency of occurrence and their impact on a variety of elements at risk. As these judgements are based on the knowledge, experience and understanding of the assessor, it is not unusual for different assessors to make different judgements about the level of risk.

The thought process used in establishing likelihoods, consequences and determining spatial and temporal factors for properties has been documented for transparency. The structure of the risk assessment process is well defined and values for some input parameters have been tabulated to guide standard approaches by different assessors. However, this should not be mistaken for precision given the limitations of the inputs outlined above. Generally, the levels of likelihoods and risks should be thought of as being within a range of typically +/- half an order of magnitude.

While the basis for the judgements contained in this report are well documented, and the levels of risk considered to be good representations of reality, the accuracy and precision of the process should not be overestimated and should always be used in an appropriate manner in combination with risk management including mitigation and treatment options.

3. Hazard Characterisation

AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This is generally a predictive exercise based on knowledge and understanding of the geological and geomorphological setting with a view to assembling historical evidence for past hazard events.

3.1 Defining the Most Likely Significant Landslide

Following Cyclone Gabrielle, small landslides within the Muriwai area were often noted to be shallow translational slides developed in the upper residual profile of the Awhitu Sand Formation which, under saturation, transition into debris flows. Detailed analysis by GHD of the mapped landslides within the Karekare and Piha areas, which included size, estimated volume, travel distance and travel angle, was undertaken to characterise the nature and distribution of landslides following the rainfall events that occurred in early 2023, particularly the Cyclone Gabrielle rainfall event, has been used as a basis for defining the magnitude of the ‘most significant landslide’ for the site.

A total of 80 landslides were mapped throughout Karekare and Piha following the storm events in Jan and Feb 2023. These landslides were then grouped into categories of volume in 50 m^3 increments. Results for an assessment of “frequency as categorised by volume” is shown in Figure 1 below.

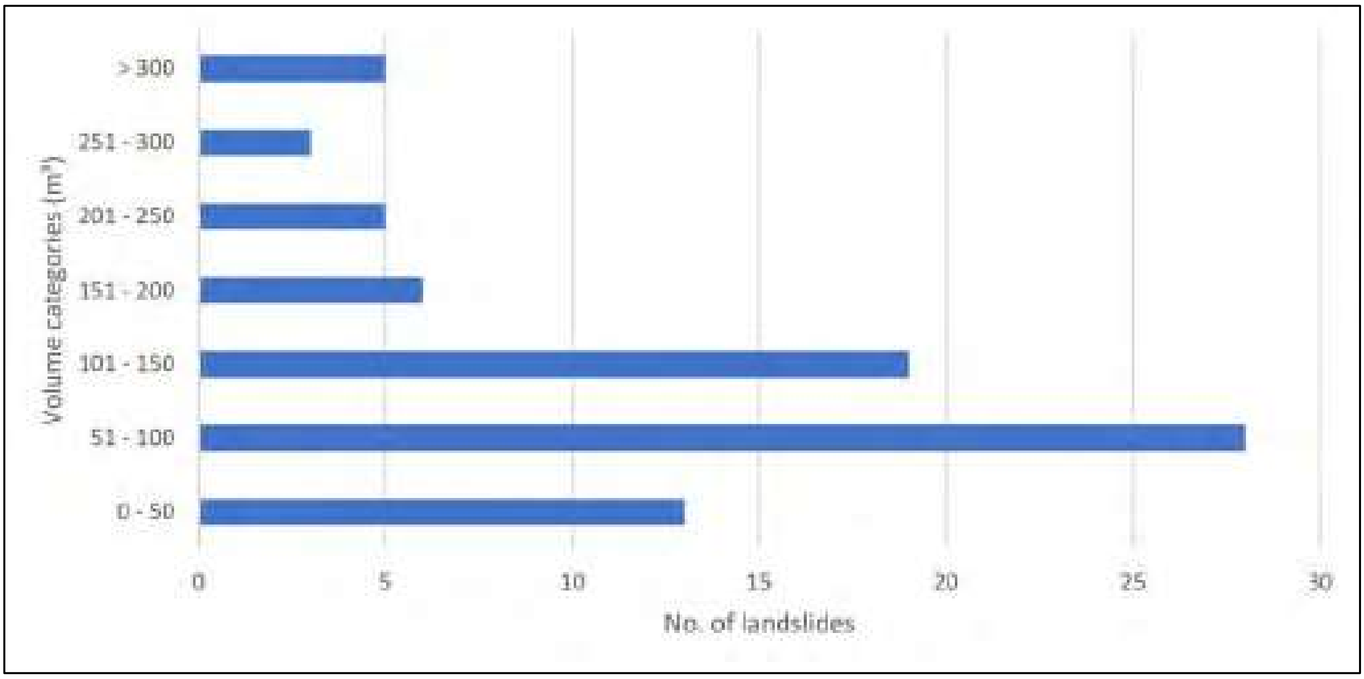


Figure A2 ***The number or frequency of mapped debris flows (on the x axis) as categorised by volume increments for mapped source areas of debris flows (on the y axis in m^3) in Karekare and Piha.***

In addition, detailed information regarding volume size, travel angle, travel distance, confinement (either unconfined or channelized) and the degree of damage caused by slides impacting dwellings and building was also collated and a number of additional graphs were developed as below:

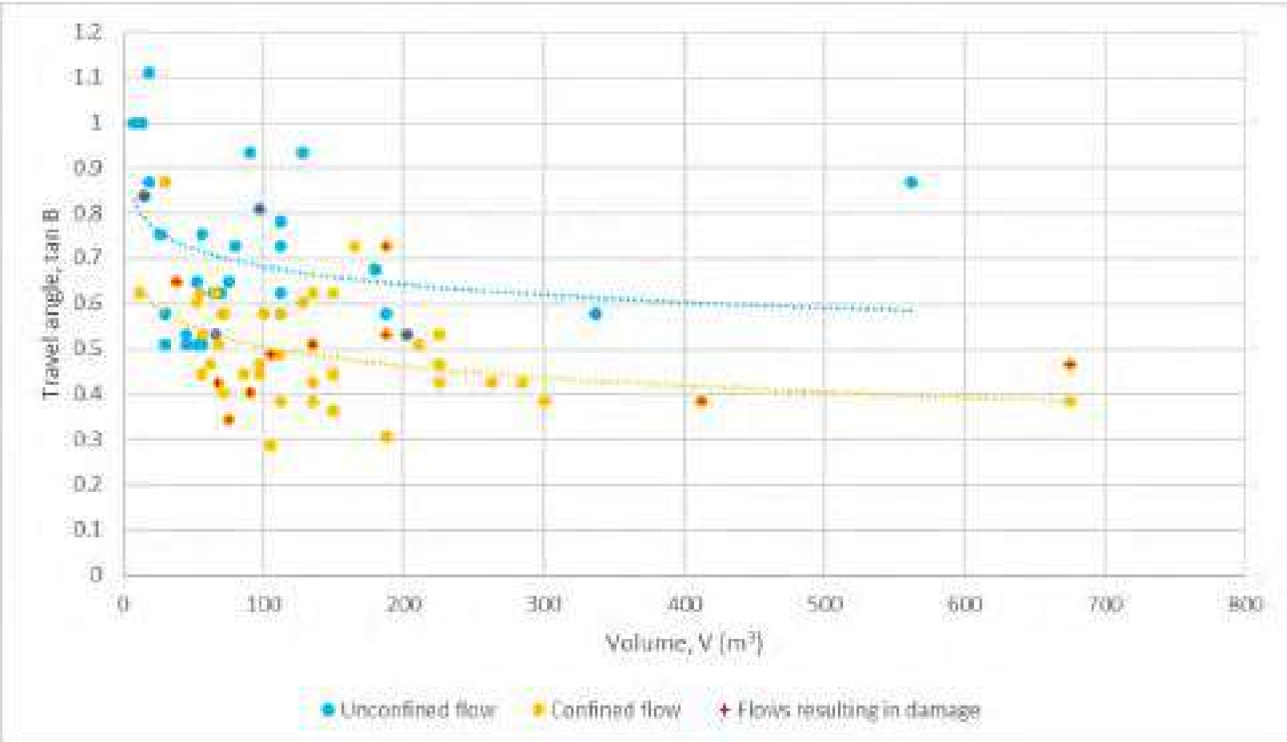


Figure A3 ***Travel angle vs volume of source area for the Karekare and Piha debris flows***

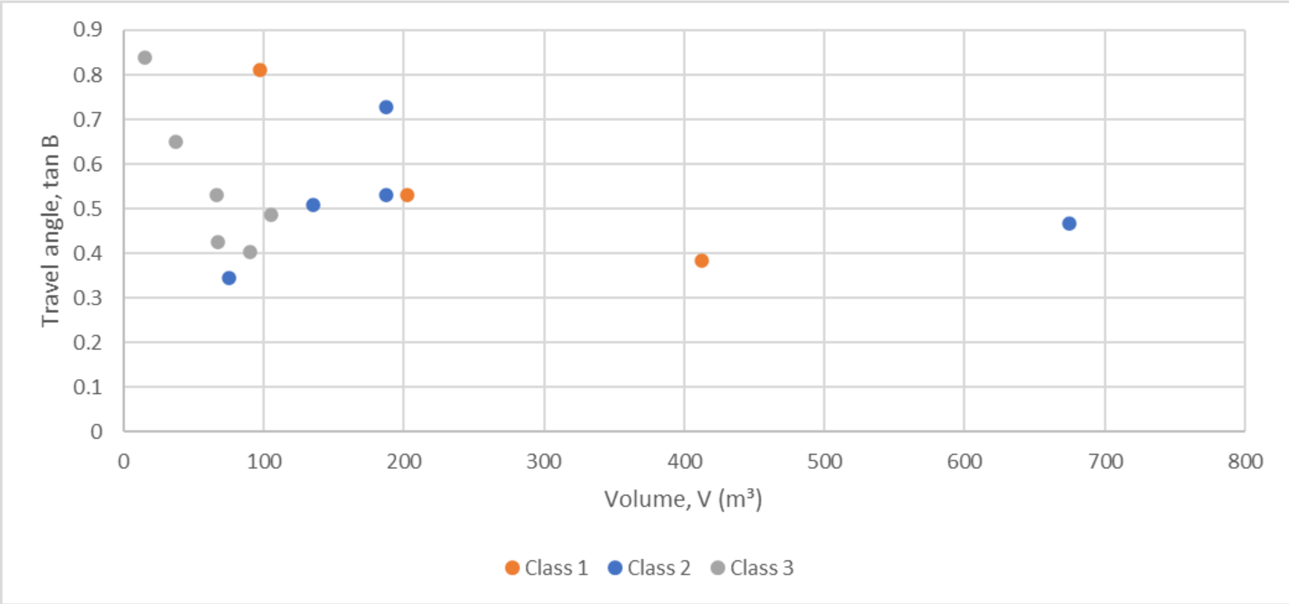


Figure A4 ***Plot of only those debris flows known to have caused some degree of damage to dwellings and buildings. Note Class 1 = Complete destruction/collapse of building, Class 2 = Partial destruction/collapse of building, significant inundation and Class 3 = Limited damage to building but no collapse or inundation, damage is other property infrastructure e.g., access stairs.***

This assessment highlights a number of important points relating the nature of these hazards including:

- Whilst a range of volumes of source areas for debris flow was noted, the most common or likely sized event was of the order of 50-100 m^3 as determined by the frequency plot.
- Many smaller volume source areas for debris flows (less than 75 m^3) typically only caused some lesser damage to buildings but once the volume increased above 100 m^3, then the vast majority of debris flows were noted to have caused partial or full collapse of dwellings and buildings.
- The greater the volume of the source area, the lower the travel angle and the greater the runout or travel distance.
- Unconfined debris flows generally have a higher travel angle compared to confined or channelized debris flows of the same volume. This means that confined or channelised debris flows have a longer runout or travel distance and hence have more potential to impact elements at risk further down the slope.

Based on this site-specific data and analysis, GHD has adopted a working definition for these risk assessments of what is termed the **most likely significant landslide** as follows:

- The volume of most likely significant landslides is assumed to be 100 $m^{3.}$
- This volume has been shown to cause significant building damage resulting in partial to full dwelling and building collapse.
- As a result, this hazard is considered to have a high probability for causing loss of life.
- Where this hazard is unconfined, the adopted travel angle based on Figure 3 has been taken as Tan (B) = 0.69 or approx. = 35°
- Where this hazard is confined or channelised the adopted travel angle based on Figure 3 has been taken as Tan (B) = 0.50 or approx. = 26.5°
- Comparison with Figure 6 from Hunter and Fell (2002) suggests the site derived travel angles are generally consistent with other data presented in that plot.

The definition of the **most likely significant landslide** is considered to be a reasonably conservative but not overly cautious estimate of the potential hazard that may affect the site. This is based on an assessment of an overview of landslides that GHD has observed in Muriwai, Karekare and Piha in 2023.

It is noted however that in some specific circumstances, larger recent debris flows may have occurred in close proximity to the site under investigation. As such, where there is evidence for a larger hazard, the assessor may

choose to adopt a larger volume event based on judgement and knowledge of that particular site. In this case other values for travel angle can be read from Figure 3.

IMPORTANT NOTE: It is duly acknowledged that volume alone does not necessarily account for the full potential of a debris flow to cause significant damage and other factors such as the degree of channelization, the additional entrainment of volume within a channel, the degree of saturation of the debris materials, the location of the source area on the hillslope, the direction of travel, the distance of travel and the velocity of the hazard at the point of impact all play important roles in the destructive capacity of any debris flow. Some of these factors are considered within the risk assessment process as conditional probabilities in spatial considerations.

3.2 Description of Other Landslide Types

As discussed in the scope of the covering report, other landslide hazards may exist at the site under assessment. These may include existing geohazards that have resulted from recent failures with the potential to pose risk to life in the immediate short-term (i.e. within the next few years) such as regression of translational failures to occur downslope of dwelling, failure of over-steepened fill and cut slopes, rockfall hazards associated with exposed rock faces/headscarps and/or loose debris remaining upslope of dwellings.

In addition, other possible geotechnical slope instability hazards relating to modified slopes (i.e. human made) may also exist and have potential to pose a risk to life - such as failures of fills, cuttings and failed retaining walls. This represents hazards that may have a range of likelihood from almost certain to possible.

Where appropriate, descriptions and definitions for each of these hazards are provided in the covering report on a case-by-case basis and will be specific to the observed hazard and actual conditions at this site.

3.3 General Descriptors for Size Classification of Landslides.

Generalized or relative descriptions of size classification systems for landslides vary significantly depending on the country of origin and the nature of the landslide hazards typically encountered. For the purposes of these assessments, GHD proposes to use the following size classification descriptions adopted from the Transport for New South Wales (TfNSW) Guide to Slope Risk Analysis Version 4 (TfNSW 2014) (see Table 3.1 below).

Table A3.1 Landslide size classification

Relative size term	Volume range	Typical mid-range dimensions (width x length x depth in metres)
Very small	<20 m3	4 x 4 x 0.5
Small	20 to 200 m3	10 x 10 x1
Medium	200 to 2000 m3	20 x 20 x 2.5
Large	2000 to 20000 m3	40 x 40 x 5
Very large	>20,000 m3	60 x 60 x 8

4. Likelihood $P_{(H)}$

Likelihood or annual probability of occurrence of the landslide, $P_{(H)}$, is one of the most critical but difficult to estimate factors as part of the risk assessment process.

4.1 The Most Likely Significant Landslide

The recent flood / storm events, the estimation of recurrence intervals for that event and the occurrence of the observed hazards form the basis for the current estimated probability of occurrence for the most likely significant landslide hazard. However, observations of the recent events noted that not all similar slopes failed as a result of

the initiating storm event and as such, an additional consideration for probability of occurrence has been included within the analysis by using conditional probabilities as follows:

$$P_{(H)} = P_{(H'1)} \times P_{(H'2)}$$

Where:

$P_{(H'1)}$ = Probability that the rainfall threshold for the most credible significant landslide is exceeded which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or 0.01 (see analysis and discussion by Auckland Council below) or 1 in 50 or 0.02 under the influence of future climate change.

$P_{(H'2)}$ =Probability that the slope for the specific assessment fails, which relates to how many of the actual slopes failed out of the total number of all slopes present. This probability is typically based a on spatial analysis of the total area of failed landslides slopes compared to the total area of all slopes for the geomorphic setting in which the site is located.

4.2 Auckland Council Guidance on Frequency for Most Likely Significant Landslide

Council provided GHD with an assessment of available rainfall data associated with Cyclone Gabrielle (Auckland Council 2023) (AC memo). During Cyclone Gabrielle, the tipping bucket rain gauge at Muriwai failed and was inundated by flood waters. The AC memo also provided rainfall analysis using AC's Quantitative Precipitation Estimate (QPE) Rain Radar System, which is a real-time rainfall product that utilises the MetService radar. The rainfall data presented by AC indicates a peak rainfall total for Muriwai during the event of 146.9mm, 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 as a result of the relatively short statistical rainfall records available in New Zealand. For the other durations modelled, the rainfall was below the 100-year event.

The AC memo recommended that an envelope of "risk" is estimated as the ARI figures will change over time and as these events are incorporated into the statistical record. The AC memo states that in general, it is considered reasonable to consider the Cyclone Gabrielle event to be in the range of 100-250 year ARI. For this assessment we have assumed that the annual likelihood of a landslide event occurring that is similar in magnitude to the February 2023 event, is about 1 in 100 (i.e., 0.01). This is considered to have a *likely* probability of occurrence.

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 are difficult to quantify.

The AC memo further recommended that risk assessment reports consider the potential for climate change to increase the frequency of high intensity rainfall. We understand that the National Institute of Water and Atmospheric Research (NIWA) has projected a 20% increase in rainfall intensity over the next 100 years which suggests that a 250-year ARI event could increase to a 50-year ARI event. Consequently, we have also included a sensitivity check based on a 50-year ARI event.

We draw the reader's attention to Section 3 of this report and reiterate that AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This report has conformed to this requirement and assessed landslide hazards that were observable during the site mapping and/or able to be interpreted via other means such as readily available aerial photographs, lidar data etc. It should be recognised that specific hazards such as rockfalls, failed retaining walls, over-steepened cuts/fill batters may have likelihoods in the *Certain to Almost Certain* range and are more likely to occur in the short term.

4.3 Other Landslide Hazards

Where other slope failures and instabilities as described in Section 3.2 are considered, individual assessments of $P_{(H)}$, the probability of occurrence, are made on the basis of expert judgment, performance of similar landslides in the area and recent site observations.

When considering hazards that may pose immediate or short-term risks to life it is probable that such hazards will have high likelihoods of occurrence that could be triggered by relatively frequent events. As a result, such hazard may have likelihoods in the *Certain to Almost Certain* range as per the ASGS2007 qualitative descriptors for likelihood.

5. Probability of Spatial Impact $P_{(S:H)}$

The AGS definition of spatial probability is represented by single term $P_{(S:H)}$ and is described as the probability of spatial impact by the landslide on the element at risk, given the landslide occurs and taking into account the travel distance and travel direction.

5.1 The Most Likely Significant Landslide - Upslope of Site

A number of conditional factors may be involved in the spatial distribution for the most likely significant landslide, and for further transparency, the following methodology has been adopted:

$$P_{(S:H)} = P_{(S':H'1)} \text{ x } P_{(S':H'2)}$$

Where:

– $P_{(S':H'1)}$ = The probability that if the landslide occurs it travels in the direction of the site under assessment. If the slopes above are consistent, and planar then probability is assumed to be 0.8 to 1.0 depending on the topography; if the originating landslide enters a channel that is directed onto the property then probability is assumed to be 1.0, or if the landslide enters a channel that is directed away from the sites then the probability is assumed to be 0.05 taking account of a small probability that the landslide may super elevate and leave the channel.

– $P_{(S':H'2)}$ = The Probability that if the landslide occurs it will travel to at least the site under assessment and will impact the property. This is to be based on two considerations as follows:

1. Modelled Behaviour based on travel distance analysis undertaken by GHD for 80 observed landslides slides in the Karekare and Piha areas (see Figure A3). Either probability = 1.0 if the travel angle projects past the dwelling, = 0.5 if the travel angle projects to the rear of the dwelling or = 0.0 if the travel angle falls short of the dwelling.

And/or

2. Observational behaviour: based on site observations of whether the previous landslides within close proximity to the study site, travelled sufficient distance to reach the site under assessment; if yes Probability = 1.0, if no, then probability = 0

– NOTE 1: The GHD analysis of travel distance highlights the effect of channelisation which shows confined debris flows travel further (i.e., they have a lower travel angle) than those which are unconfined on consistent or planar slopes. Such considerations are included on a site-by-site basis. Interestingly, this event-specific analysis also generally agrees with findings presented in Hunter and Fell (2002).

– NOTE 2: Where significant debris flows have occurred in close proximity to the site under assessment, and the observed travel distance is greater than that estimated using the modelled approach, the preferred GHD approach is to use the greater of the two travel distances to assess spatial impact.

5.2 The Most Likely Significant Landslide – Under the Dwelling/Building and/or Downslope Below the Dwelling/Building

Based on the possible failure area:

- If the failure area is > ~5 m from the dwelling then the value for $P_{(S:H)}$ will be 0 as a landslide occurring at that location will not impact dwelling. (The general assumption is that the landslide headscarp would have a length of 5m based on size of most likely significant landslide).
- If the failure area is within ~5m from the dwelling (like above) then the value for $P_{(S:H)}$ will be 0.5 to account for uncertainty of it encroaching within the footprint of the dwelling.
- If the failure area encompasses a significant portion of the dwelling then the value for $P_{(S:H)}$ will be 1.0 as there is a certain probability it will impact the dwelling.

Estimates of how far back the most significant landslide will regress are difficult to model without a detailed slope stability analysis and sufficiently accurate soil and rock inputs. This would require an intrusive geotechnical investigation which is outside the scope of this study.

GHD has adopted a more empirical approach that assesses the spatial extent of lateral downslope movement of the most likely significant landslide based on direct observations of existing landslides in close proximity to the site under assessment. In the absence of other information, a similar extent of regression has been applied to any future slides. An estimate of $P_{(S:H)}$ can then be made as to the potential interaction with the element at risk.

5.3 Other landslides – Upslope of the study site

Other types of potential landslides situated above dwellings and buildings on the site under assessment, should be assessed in a similar manner to the most likely significant landslide. Estimates of travel distance are taken from Hunter and Fell (2002) and/or previous local knowledge and/or observation of similar landslides in the area.

When undertaking short term assessments, hazards involving reactivation of existing landslides that are located upslope of the study site that didn't previously reach the site must be taken account. In addition, remobilisation of debris from any upslope landslides must also be assessed for their potential of runout or travel distance using Hunter and Fell (2002).

Similarly potential failures of modified slopes such as cuttings or fills located above or directly adjacent to dwellings and buildings must also be assessed for their spatial impact and the methods of assessment follow the same approach.

5.4 Other landslides – under buildings and downslope of the building

A similar approach to that taken for other landslides upslope has been adopted. Observation of existing failures and how much lateral downslope movement can be used as a proxy for what may occur in the future under a regression type scenario.

5.5 Temporal Spatial Probability $P_{(T:H)}$

These risk assessments have not considered specific occupancy scenarios for each individual residence. We acknowledge that the occupancy of each residence could vary significantly depending on the demographics of the residents and the usage of the residence. For example, some residences may be predominantly used as holiday accommodation, occupied mainly on weekends, whereas other residences could be permanently occupied by working families.

This assessment has assumed the following occupancies:

– Residences are typically occupied for 15 hours each day during weekdays;
– On weekends, residences are occupied for about 20 hours each day;

– The percentage of time a residence is occupied is therefore about 68%.

Any further delineation of the spatial variations in occupancy (i.e. if a bedroom is at the front or the rear of the house etc) are not considered feasible or warranted within the context of the precision of this assessment.

6. Vulnerability $V_{(D:T)}$

6.1 Most likely significant Landslide

AGS (2007c) includes a table of vulnerability values for various inundation and building damage scenarios as adapted by Finlay et al (1999). It is important to note that the AGS (2007c) vulnerability table doesn't adequately cater for all the building damage scenarios GHD has observed in Muriwai, Karekare and Piha. GHD has therefore further adapted this table and combined it with information from the TfNSW Guide to Slope Risk Analysis (2014) as well as observations of damage to buildings and structures resulting from the recent landslides in Muriwai, Karekare and Piha.

The table of vulnerability values used in this assessment is presented in Table A6.1. These values have been used as a guide and expert judgement has been applied to select a value within the range of values where appropriate on a site-specific basis.

Table A6.1 Summary of Vulnerability Values adopted

Case	Range	Typical value to be used in this assessment	Comments
Person in a building that collapses under impact from debris flow	0.8 -1.0	0.9	Death is almost certain. Evacuation unlikely to occur
If building is inundated with debris and the person is buried	0.8 -1.0	0.8	Very high potential for death Evacuation unlikely to occur
If building is inundated with debris but no collapse occurs and the person is not buried	0.01 -0.1	0.1	High chance of survival Evacuation unlikely to occur
If the debris strikes the building only	0.001-0.05	0.01	Very high chance of survival
If failure occurs below the building and results in significant collapse	0.5-0.8	0.6	Moderate to high potential for death. No forewarning signs with evacuation unlikely to occur.
If failure occurs below the building and results in partial collapse	0.01 -0.1	0.05	High chance of survival. Signs of building distress should provide occupants with opportunity to take evasive action.
If failure occurs below the building and results in damage. No collapse occurs.	0.001-0.05	0.005	Very high chance of survival. Evacuation almost certain.

7. Risk Evaluation

The main objectives of risk evaluation are usually to compare the assessed risk to risk levels that are acceptable or tolerable to the community, and therefore to decide whether to accept, tolerate or treat the risks and to set

priorities for remediation. The Tolerable Risk Criteria are usually imposed by the regulator, unless agreed otherwise with the owner/client. AGS (2007d) provides discussion and gives the AGS recommendations in relation to tolerable risk for loss of life. These are summarized in the table below.

Table A7.1 AGS Suggested Tolerable loss of life individual risk.

Situation	Suggested Tolerable Loss of Life Risk for the person most at risk
Existing Slope / Existing Development	10^{-4} per annum (1E-4 pa) or 1 in 10,000 pa
New Constructed Slope / New Development / Existing Landslide	10^{-5} per annum (1E-5 pa) or 1 in 100,000 pa

It is important to distinguish between “acceptable risks” and “tolerable risks”. AGS (2007c) states that tolerable risks are risks within a range that society can live with so as to secure certain benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if practicable. Acceptable risks are risks which everyone affected is prepared to accept. Acceptable risks are usually considered to be one order of magnitude lower than the Tolerable risks.

8. References

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.

Australian Geomechanics Vol 42 No 1 March 2007 Extract “Practice Note Guidelines for Landslide Risk Management 200” AGS (2007c)

P J Finlay, G R Mostyn & R Fell (1999). ‘Landslides: Prediction of Travel Distance and Guidelines for Vulnerability of Persons’. Proc 8th. Australia New Zealand Conference on Geomechanics, Hobart. Australian Geomechanics Society, ISBN 1 86445 0029, Vol 1, pp.105-113.

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

New South Wales Government, Transport for New South Wales ‘Guide to Slope Risk Analysis’ Version 4, April 2014.

Appendix B

Glossary of Terms

DEFINITION OF TERMS

Acceptable Risk – A risk which, for the purposes of life or work, society is prepared to accept as it is with no regard to its management. Society does not generally consider expenditure in further reducing such risks justifiable.

Authority or **Council** having statutory responsibility for community activities, community safety and development approval or management of development within its defined area/region

Consequence – The outcomes or potential outcomes arising from the occurrence of a landslide expressed qualitatively or quantitatively, in terms of loss, disadvantage or gain, damage, injury or loss of life.

Creep Failure – A time-dependant deformation mechanism where constant stress is applied to a material. Creep failure can be identified by ridges the ground surface and curved tree trunks.

Dropout – A landslide feature occurring along the length of the road-side on the downslope edge. Drop outs can result in the undermining the road carriageway.

Elements at Risk – The population, buildings and engineering works, economic activities, public services utilities, infrastructure and environmental features in the area potentially affected by landslides.

Entrainment – The process of surface sediment transportation through water and mass movement.

Frequency – A measure of likelihood expressed as the number of occurrences of an event in a given time. See also Likelihood and Probability of Occurrence.

Hazard – A condition with the potential for causing an undesirable consequence. The description of landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached material, and the probability of their occurrence within a given period of time.

Individual Risk to Life – The risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide or who follows a particular pattern of life that might subject him or her to the consequences of the landslide.

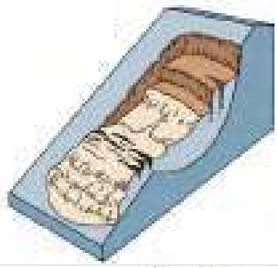
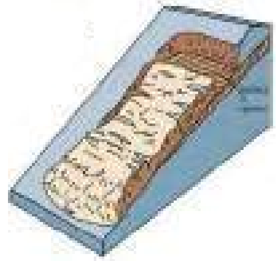
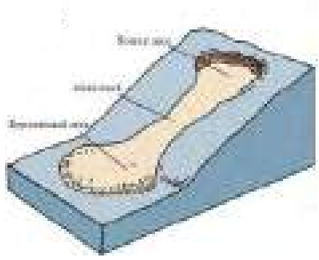
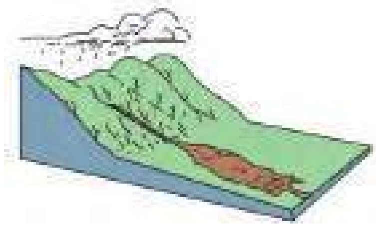
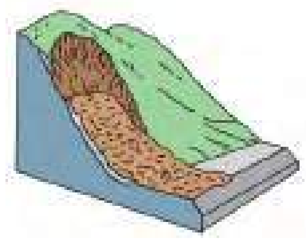
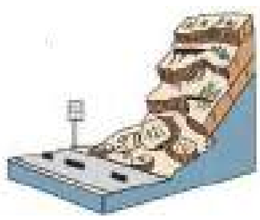
Landslide - A landslide is defined as the movement of a mass of rock, debris, or earth down a slope. The most widely used landslide classification system is that proposed by Cruden and Varnes in 1996 (after Varnes 1954 and Varnes 1978). This has been updated by Hungr, et al., 2014. In its most simple form two nouns are used to describe, firstly the type of material involved and secondly, the mechanism of failure, i.e., rock fall, debris flow.

Landslide inventory – An inventory of the location, classification, volume, activity and date of occurrence of landsliding

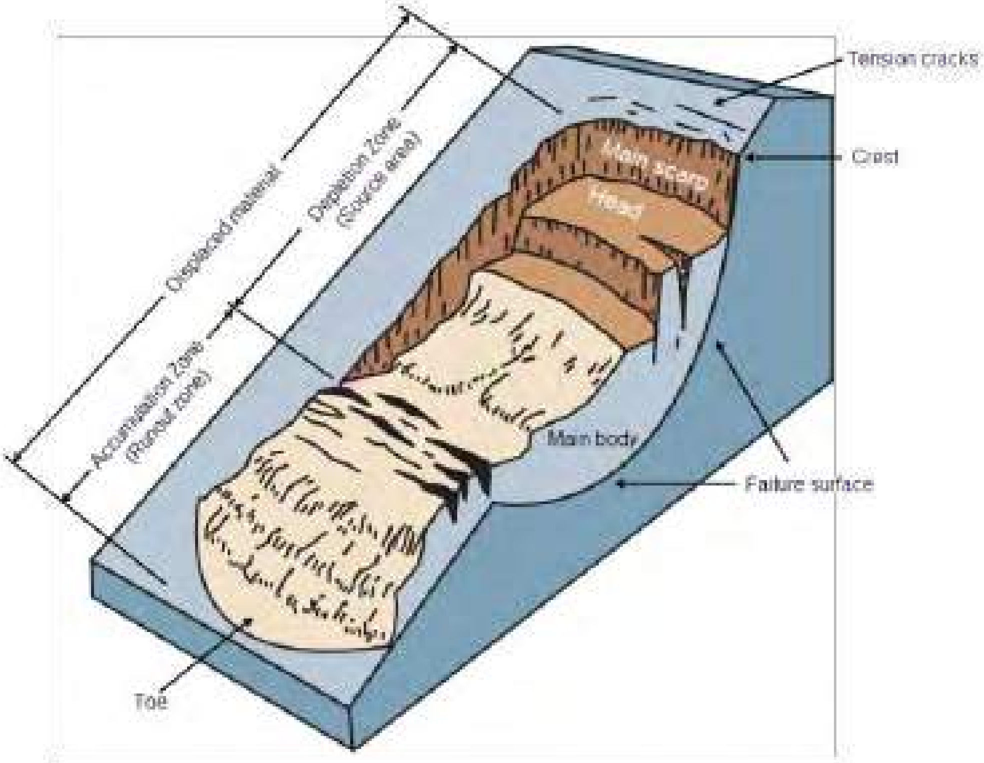
Landslide Risk - Landslide risk is defined herein as the likelihood that a particular landslide will occur and the possible consequences to a specific element at risk (property or human life) taking account of both spatial and temporal considerations.

Landslide Susceptibility – A quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding.

Landslide Classification – Referenced from Varnes, 1978.

Landslide Type	Landslide Description	Illustration
Rotational sliding	The landslide failure surface is curved concavely upward and the movement of mass is mainly rotational. Rotational movement causes back tilting of the displaced material near the headscarp.	
Translational sliding	The landslide mass moves along a planar failure surface with minor rotational movement.	
Earth flow	The movement of saturated fine-grained materials or clay bearing rocks. The displaced material forms a characteristic hourglass shape with an elongated flow path.	
Debris flow	The rapid movement of saturated, loose material caused by heavy precipitation and surface water flow. Commonly occurring on steep slopes.	
Debris avalanche	A type of debris flow that is *extremely* rapid.	
Rock fall	The separation of rocks and boulders along fractures, joints and bedding planes on steep slopes or cliffs. The movement is heavily influenced by mechanical weathering of the rock mass and gravity.	

Landslide characteristics – Modified after Varnes, 1978.



Likelihood – Used as a qualitative description of probability or frequency of the event/landslide.

Overland Flow Path – The predicated flow path of stormwater over the topography.

Permeability – The capacity of a material to allow water to pass through it. Clay materials are impermeable whereas gravels and sands are porous and therefore permeable.

Probability – A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the magnitude of the uncertain quantity or the likelihood of the occurrence of the uncertain future event. There are two main interpretations:

(i) Statistical – frequency or fraction – The outcome of a repetitive experiment of some kind like flipping coins. It also includes the idea of population variability. Such a number is called an "objective" or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment.
(ii) Subjective probability (degree of belief) – Quantified measure of belief, judgement, or confidence in the likelihood of a outcome, obtained by considering all available information honestly, fairly and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation or the quality and quantity of information. It may change over time as the state of knowledge changes.

Probability of Occurrence – used interchangeably with Likelihood.

Quantitative Risk Analysis – an analysis based on numerical values of the probability, vulnerability and consequences, and resulting in a numerical value of the risk.

Recurrence Interval (repeat period) – An estimated value of how often an event occurs based on the average time between passed events.

Regression – The continual movement of a landslide downslope and or widening/retreat of the headscarp.

The **Regulator** will be the responsible body/authority for setting Acceptable/Tolerable Risk Criteria to be adopted for the community/region/activity, which will be the basis for setting levels for Acceptable and Tolerable Risk in the application of the risk assessment guidelines.

Risk – A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by the product of probability x consequences. However, a more general interpretation of risk involves a comparison of the probability and consequences in a non-product form.

Risk Analysis – The use of available information to estimate the risk to individuals, population, property or the environment from hazards. Risk analyses generally contain the following steps: scope definition, hazard identification and risk estimation.

Risk Assessment – The process of risk analysis and risk evaluation.

Risk Control or Risk Treatment – The process of decision making for managing risk and the implementation or enforcement of risk mitigation measures and the re-evaluation of its effectiveness from time to time, using the results of risk assessment as one input.

Risk Estimation – The process used to produce a measure of the level of health, property or environmental risks being analysed. Risk estimation contains the following steps: frequency analysis, consequence analysis and their integration.

Risk Evaluation – The stage at which values and judgements enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks.

Risk Management – The complete process of risk assessment and risk control (*or risk treatment*).

Runout Distance – The horizontal distance from the source area to the distal toe.

Susceptibility – see Landslide Susceptibility

Temporal-Spatial Probability – The probability that the element at risk is in the affected area at the time of the landslide.

Tolerable Risk – A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if possible.

Transgression-regression cycles – Sedimentary deposits formed from cycles of sea level rise and fall.

Travel Angle – The angle from the crest of the source area to the distal toe of the debris (run out zone)

Vulnerability – The degree of loss to a given element or set of elements within the area affected by the landslide hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss). For property, the loss will be the value of the damage relative to the value of the property; for persons, it will be the probability that a particular life (the element at risk) will be lost, given the person(s) is affected by the landslide.

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→ The Power of Commitment

Appendix E-4

207 Motutara Road Landslide Risk Assessment

Waitākere Coastal Communities Landslide Risk Assessment

207 Motutara Road, Muriwai

Auckland Council

30 April 2024

→ The Power of Commitment

Project name	AC Geo Panel - Waitākere Coastal Communities LHRA
Document title	Waitākere Coastal Communities Landslide Risk Assessment | 207 Motutara Road, Muriwai
Project number	12612462
File name	12612462- RiskAssess207 Motutara Rd MuriwaiFINAL.docx

Status Code	**Revision**	**Author**	**Reviewer**		**Approved for issue**		
			Name	**Signature**	**Name**	**Signature**	**Date**
S4	0	Ryan Hayes	Don Macfarlane		Matt Howard		30/04/2024
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[Status code]							
[Status code]							

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1. Introduction

1.1 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 turned into saturated debris flows as they travelled downslope. These flows 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 February 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).

GHD has been engaged by Auckland Council (AC)[1] to carry out landslide risk assessments and to provide associated landslide risk management advice and geotechnical investigations recommendations in the Waitakere area, specifically for the residential areas of Muriwai, Piha and Karekare. These assessments were necessary due to widespread, damaging landslides associated with Cyclone Gabrielle in February 2023. GHD has completed a landslide risk assessment[2], whereby some properties were identified as having an unacceptably high risk of being impacted by future large landslides.

1.2 Purpose of this report

The residential property at 207 Motutara Road, Muriwai ('the site') has been assessed by GHD as having an acceptable risk from large scale landslides[3] (see the November 2023 report). However, a localised, damaging landslide occurred, and the purpose of this assessment is to carry out a Quantitative Landslide Risk Assessment (QRA) to estimate the risk of Loss of Life to individuals at the property from local landsliding. The outcome of the QRA will be used to inform subsequent property risk categorisation and building placard designation review by AC.

1.3 Scope

The scope of work requested by AC was as follows:

- Review available historical and recent imagery, including LiDAR.
- Review pertinent historical data and GHD work undertaken as part of the wider Muriwai landslide risk assessment reported in GHD (2023).
- Undertake a site engineering geological assessment of landslide hazards at the impacted property.
- Undertake a QRA where landslide hazards have been identified that pose a Loss of Life landslide risk using the Australian Geomechanics Society Practice Note Guidelines for Landslide Risk Management, commonly known as AGS (2007c).
- Deliver report(s) documenting the QRA inputs and outcome.

Specifically excluded are an assessment of property risk, site specific subsurface geotechnical investigations, service inspections, and groundwater monitoring.

This assessment considers geotechnical matters only. There may be other non-geotechnical considerations that affect the final property risk categorisation or placard designation of which GHD are not aware, such as flood risk and structural damage to property.

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[1] Under Contract CW198379, Master Services Agreement CCCS: CW74240 dated 7/09/2019
[2] Dated 03/11/2023, document file ref 12612462_Overall Report FINALRev0.docx
[3] In the GHD November 2023 report, 'large scale' landslide hazards refers to landslides originating from the main escarpment that typically have a volume of more than about 50 m3 with the potential to cause total or partial collapse of a dwelling.

Identification of options for the mitigation of geotechnical hazards has not been undertaken as part of this study.

Although considered unlikely, GHD reserves the right to amend the opinions, conclusions and recommendations provided within this report, should additional geotechnical information become available.

1.4 Our Approach

GHD have completed a landslide risk assessment for Muriwai which assessed the risk to life of large-scale landslide hazards to inform possible future dwelling hazard designations. The assessment was limited to 'large scale' landslide hazards originating from the main escarpment located to the south-east of Muriwai because the initial placard assessment was largely aimed at mitigating risks associated with these.

Smaller, more localised landslide hazards that could originate (or may have already initiated) from other areas in Muriwai such as within the footprint of individual residential properties were not considered in the overall risk assessment. However, these have the potential to cause damage to dwellings and subsequently pose a risk to life for residents, partly due to the relatively steep topography and the potential for high travel velocity.

The approach of identifying landslide hazards over large and common source areas, such as that used for the November 2023 Muriwai assessment, does not capture numerous, smaller scale, localised landslides. For this reason, a QRA is presented for the individual property (207 Motutara Road) based on an assessment that includes site observations and a desktop review of available information. The results aid with informing the QRA with regards to the presence of existing and historical landslide hazards and site-specific slope conditions.

The QRA undertaken for this report only assesses risk to life to occupants of the dwelling due to landsliding. The assessment considers a number of hazard scenarios as follows:

1. the **most likely significant landslide hazard** based on the observed hazards with respect to the mapped landslides and their distribution within the broader landscape. In addition, considerations of the hazard relationship to topography, position on the hillslope and proximity to the elements at risk are also included. This represents a credible hazard scenario following a triggering event with a similar frequency as the February 2023 event.
2. Existing geohazards that have resulted from recent failures with the potential to pose risk to life, such as regression and/or remobilisation of translational failures that are upslope or downslope of a dwelling, or failure of oversteepened fill and cut slopes. These represent hazards that exist at the site and may be triggered by a more frequent event in the range of *certain to almost certain*[4] to occur.
3. Other possible geotechnical slope instability hazards that have potential to pose a risk to life, such as failures of fills, cuttings and failed retaining walls. These represent hazards that may have a range of likelihood from *almost certain to possible*.

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. The methodology used for the QRA is outlined in Appendix A. The site-specific input parameters and uncertainties are described in Section 3.

A glossary of terminology is presented in Appendix B.

[4] The terminology used when referencing probabilities has been adopted from the Qualitative Measures of Likelihood table for assessing risk to property in AGS (2007c). For this assessment, these terms and associated probabilities are Certain = 0.99, Almost Certain = 0.1, Likely = 0.01, Possible = 0.001, Unlikely = 0.0001, Very Unlikely = >0.00001

2. Site conditions

2.1 Site description

The site is located at 207 Motutara Road, Muriwai, legally described as Lot 1 DP 186496, and has an approximate area of 1535 m^2. A GHD engineering geologist inspected the site on 12 December 2023. No inspection was undertaken within or under the house. However, a video taken by the homeowner that was made available to us by AC provides an insight into some of the interior damage.

As shown in Figure 2.1, the affected property is located towards the northern end of the township on the western, seaward, side of Motutara Road, approximately 40 m south of Muriwai Lodge. In the area surrounding the site, Motutara Road is positioned on a bench feature which separates the approximately 70 m high, steep main escarpment to the east, and a smaller, approximately 20 m high more localised escarpment, with variably shallow to steep slopes to the east. The property spans most of this escarpment from the driveway entrance at approximately 65 m RL to its western extent at approximately 50 m RL. The slopes within the property are generally quite shallow (10-20°).

There is a single, two storey dwelling on the property which appears to have been constructed on a fill platform at approximately 54 m RL. The natural slopes surrounding the dwelling are generally quite shallow (10-20°) with the exception of the slopes beyond the northeast corner of the dwelling which rise up to Motutara Road at a moderate to steep grade (up to 40°).

Numerous ‘large’ landslides (mapped on Figure 2.1) originating from the crest and upper slopes of the main escarpment to the east of the site occurred during Cyclone Gabrielle but did not affect the dwelling, terminating at or close to Motutara Road. A smaller scale, localised failure originating from the slopes below Motutara Road, just outside (to the east) of the property boundary, at approx. 65 m RL impacted the eastern side of the dwelling.

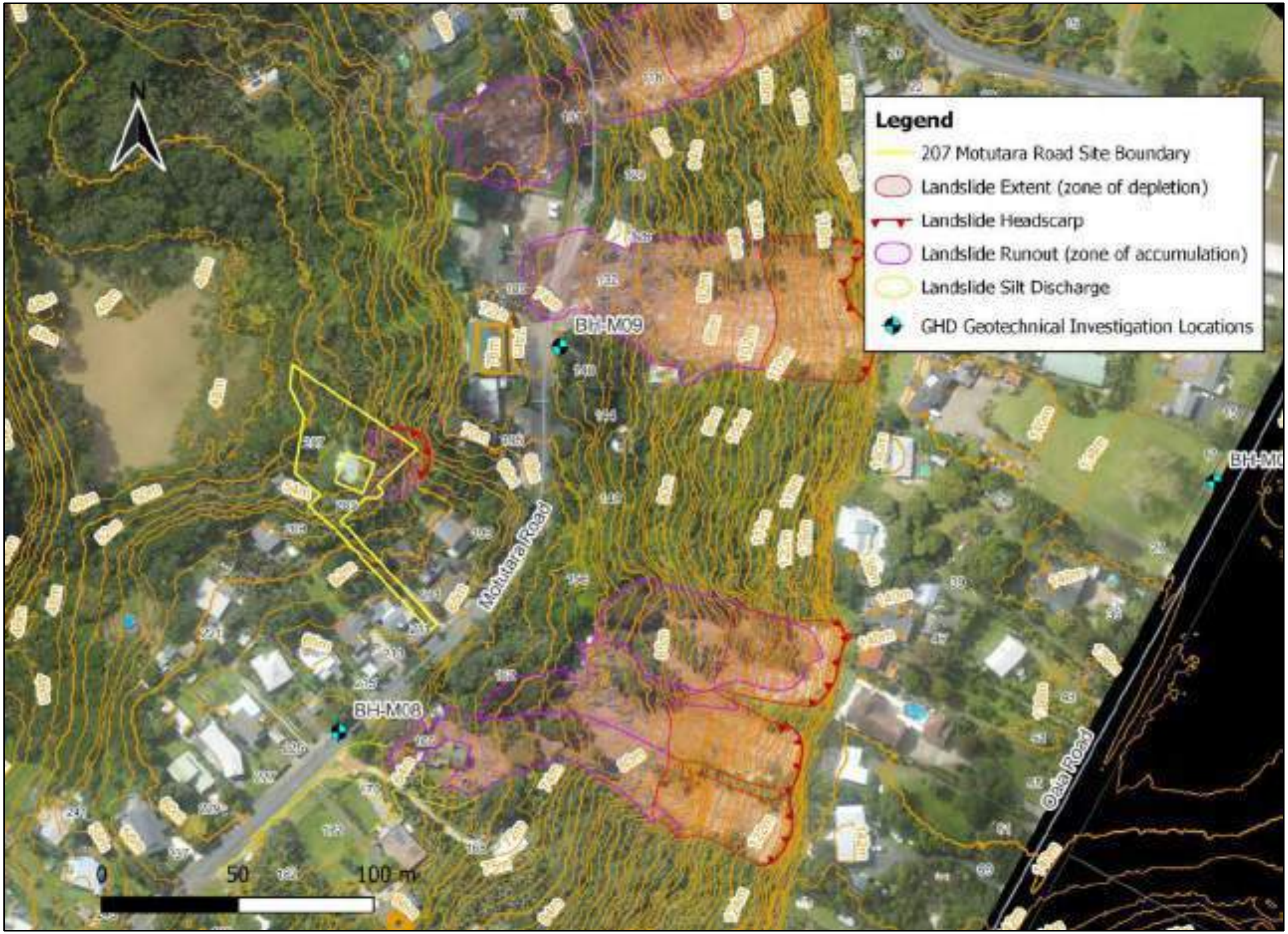


Figure 2.1 *Site location at 207 Motutara Road, Muriwai*

2.2 Site services and sources of water

Auckland Council's GeoMaps presents relevant underground services and hydrologic information for the site. An excerpt of the data is presented in Figure 2.2.

Two overland flow paths are mapped within the property boundary. One, originating outside the boundary on the slopes above the dwelling to the southeast, is mapped flowing beneath the dwelling into an open watercourse northwest of the property. The second flow path originates in the northwest corner of the property and flows into the same open watercourse. Both overland flow paths have a catchment size of approximately 2000 m^2 – 4000 m^2.

The landslide that impacted the dwelling does not appear to directly correlate with either of the mapped overland flow paths (see Figure 2.2).

No underground services associated with water are mapped on the slopes above the dwelling.

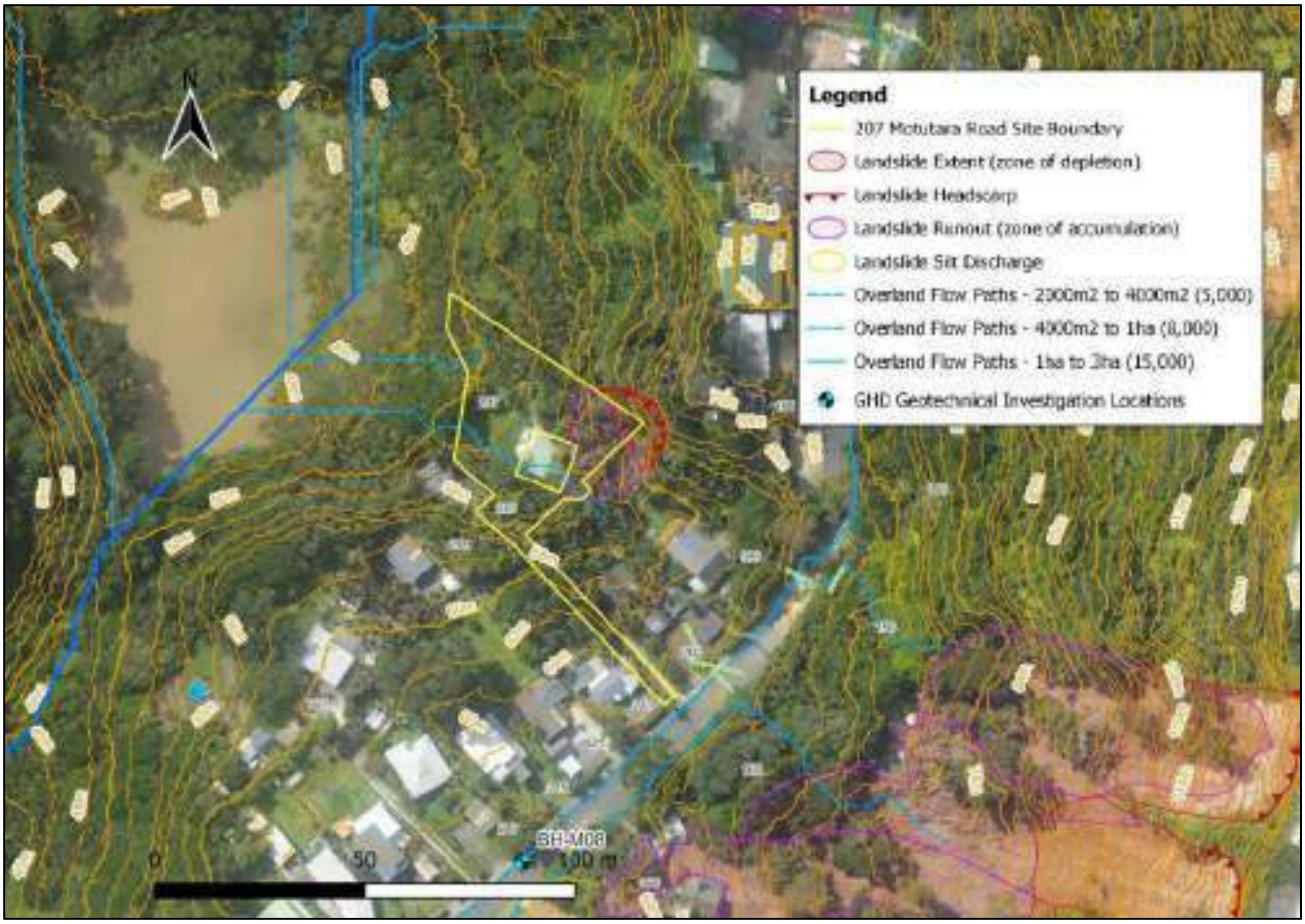


Figure 2.2 Overland flow paths and underground services for the site (source: Auckland Council GeoMaps).

2.3 Published geology

The published 1:50,000 scale geological map of the area (Hayward, 1983) indicates the site is entirely underlain by the Awhitu Sand Formation (qs), part of the Kaihu Group (Figure 2.3). More recently deposited Holocene aged (less than 10 kya) dune sands (qmf) are present at lower elevations, as part of the coastal landscape. These are approximately 100 m west of the property.

Awhitu Sands ('qs') are Pliocene aged (less than 2 Mya) characterised as 'coarse sand, clayey, often limonitised (as laterally discontinuous layers), with minor tuff, lignite and siltstone' (Hayward, 1983). The formation originated as coastal sand deposits. Awhitu Sands are generally oxidised to an orange-brown colour when exposed at the surface, resulting in a weak iron-cementation that allows for the development of large, more than 50 m high steep slopes, such as the escarpment.

The formation is weakly bedded and cross-bedded at the sub metre scale. Locally the formation is inferred to dip north and eastward at a shallow angle. Occurrences of silty/clayey horizons are occasionally visible in outcrop and have been encountered within boreholes, however it is unclear how persistent they are spatially.

Although not mapped, more recent colluvium material formed as a result of ongoing erosion and periodic landsliding associated with escarpment recession is likely present on the basal/lower slopes of the escarpment.

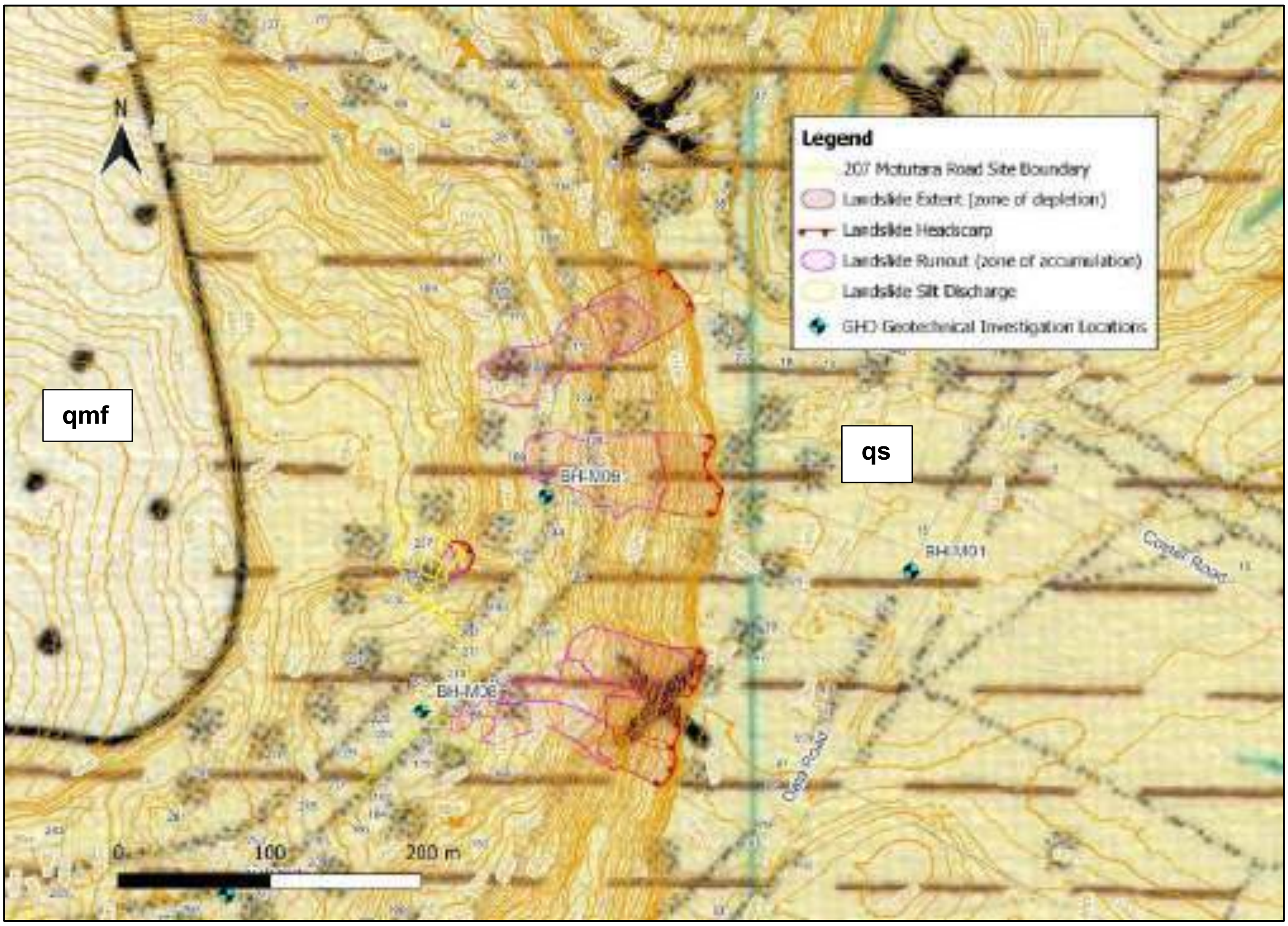


Figure 2.3 Excerpt of the Waitākere 1:50,000 scale geological map (Hayward, 1983[5]), illustrating the underlying geology at the site location.

[5] Hayward, B.W. 1983: Sheet Q11, Waitakere. Geological Map of New Zealand 1:50,000 Map

2.4 Historical data summary

A summary of the historical data relevant to 207 Motutara Road is presented in Table 2.1.

Table 2.1 Summary of historical data

	Applicable data available	Notes
Historic aerial photos	- 1940 - 1950 - 1953 - 1975 - 2000 - 2004 - 2008 - 2010-2011 - 2015-2017 - 2022	- No obvious evidence of instability was identified from the historical aerials within the property itself. - Evidence of wider scale erosion evident from 1940, where many of the spurs leading off main escarpment are bare as well as sections of the main escarpment crest. Suggests ongoing erosion of surficial soil. No regression of escarpment observed. - Photos sourced from Retrolens and Auckland Council Geomaps.
NZ Geotechnical database	Two boreholes (BH-MH08 and BH-MH09) completed by GHD in July 2023. Located approx. 50 m south (BH-MH08) and 60 m northeast of property boundary (see Figure 2.1).	- 10.95 m deep boreholes drilled at 63 m RL (BH-MH08) and 72 m RL (BH-MH09). - BH-MH08 entirely within loose to medium dense silty sand interpreted as Paleo Colluvium - BH-MH09 entirely within loose to medium dense silty sand interpreted as Awhitu Sand Formation. A <1 m band of highly weathered, extremely weak sandstone was encountered at 9.6 m
Council GeoMaps	Overland flow data from Auckland City Council ArcGIS.	- Discussed in Section 2.2.
Rapid building Assessment Geotech reporting	N/A	N/A
Independent geotechnical reports	N/A	N/A
Anecdotal information	Landowner video provided in June 2023	Incorporated into Section 2.5
LiDAR Imagery	Feb 2023 Digital Terrain Model.	- Possible historical headscarps in the escarpment suggest ongoing recession through landsliding. - Possible hummocky ground on the natural slopes above the dwelling.

2.5 Engineering geological model

2.5.1 Awhitu Sand Formation

Awhitu Sands are exposed within the entire escarpment and have generally been described as medium dense to very dense sands overlying massive, extremely weak, moderately weathered, iron-cemented fine to coarse sandstone. Irregular layers of clay and silt rich material are typically spaced every 5-10 m and relatively thin (less than 1.0 m and often less than 0.1 m). The strength profile of the Awhitu Sands displays a relatively linear increase with depth.

The in-situ nature of the Awhitu Sands suggests they are relatively permeable. However, as discussed in the November report there is also significant evidence for perched groundwater tables shown by:

- Multiple occurrences of groundwater seeps or springs emerging within the middle and base of the escarpment slope face, from above underlying (presumed aquiclude) layers of clay and silt rich beds as well as heavily oxidised iron pans
- Variable and sharply changing weathering profile with localised layers of cemented iron oxidised sand between un-oxidised material at depth.

2.5.2 General landslide characteristics

As described in the November report (GHD 2023), the landslides identified across Muriwai following the February 2023 event can be categorised into two types based on their physical characteristics as follows:

Large slips: typical headscarp widths of 30-70 m, with source and debris runout areas more than 100 m in length, often extending well past the base of the escarpment onto the flatter slopes below, and

Smaller isolated slips: generally with headscarp widths of less than 30 m and extending less than 50 m. As a result, debris from these landslides generally did not reach the base of the escarpment.

2.5.3 Landslide impacting the site

The landslide that impacted the dwelling at 207 Motutara Road is illustrated by site mapping on Figure 2.4 and is also shown in the context of different imagery on Figure 2.5 and Figure 2.6 below. An interpretive cross section through the site is presented in Figure 2.11. Ground conditions have been interpreted from a combination of historical data, site mapping and nearby geotechnical investigation data. The cross section is indicative only and may not be representative of actual conditions.

The landslide headscarp (Figure 2.7) has an approximate width of 15 m and is at an elevation approximately 15 m above the rear of the dwelling, near the crest of the localised escarpment below the topographic bench feature on which Motutara Road is located. Following a high degree of ground saturation, it initiated on a 30-40° vegetated slope as a ~ 1-2 m deep translational (with a possible rotational component) failure. The exposed headscarp has left a steeper 45-55° slope profile.

The landslide does not appear to have developed into a debris flow similar to failures seen elsewhere in Muriwai, likely due to its relatively short travel distance. A large volume (potentially up to 300 m^3) of landslide debris was deposited at the base of the slope, with a maximum thickness of approximately 2 m impacting the rear of the dwelling (Figure 2.8 and 2.9). A significant portion of the damage to the rear wall of the dwelling was caused by the entrainment of large trees within the debris (Figure 2.9). No building collapse as a result of landslide damage was noted.

Ponding of water on the body of the landslide (Figure 2.9) as well along its lateral extents has occurred following the event and a video provided by the homeowner indicates that water seepage and secondary silt discharge has entered the ground floor of the dwelling. This likely occurred during subsequent relatively frequent rainfall events as a consequence of poor drainage conditions. Figure 2.10 shows landslide debris did not flow around the sides or front of the house.

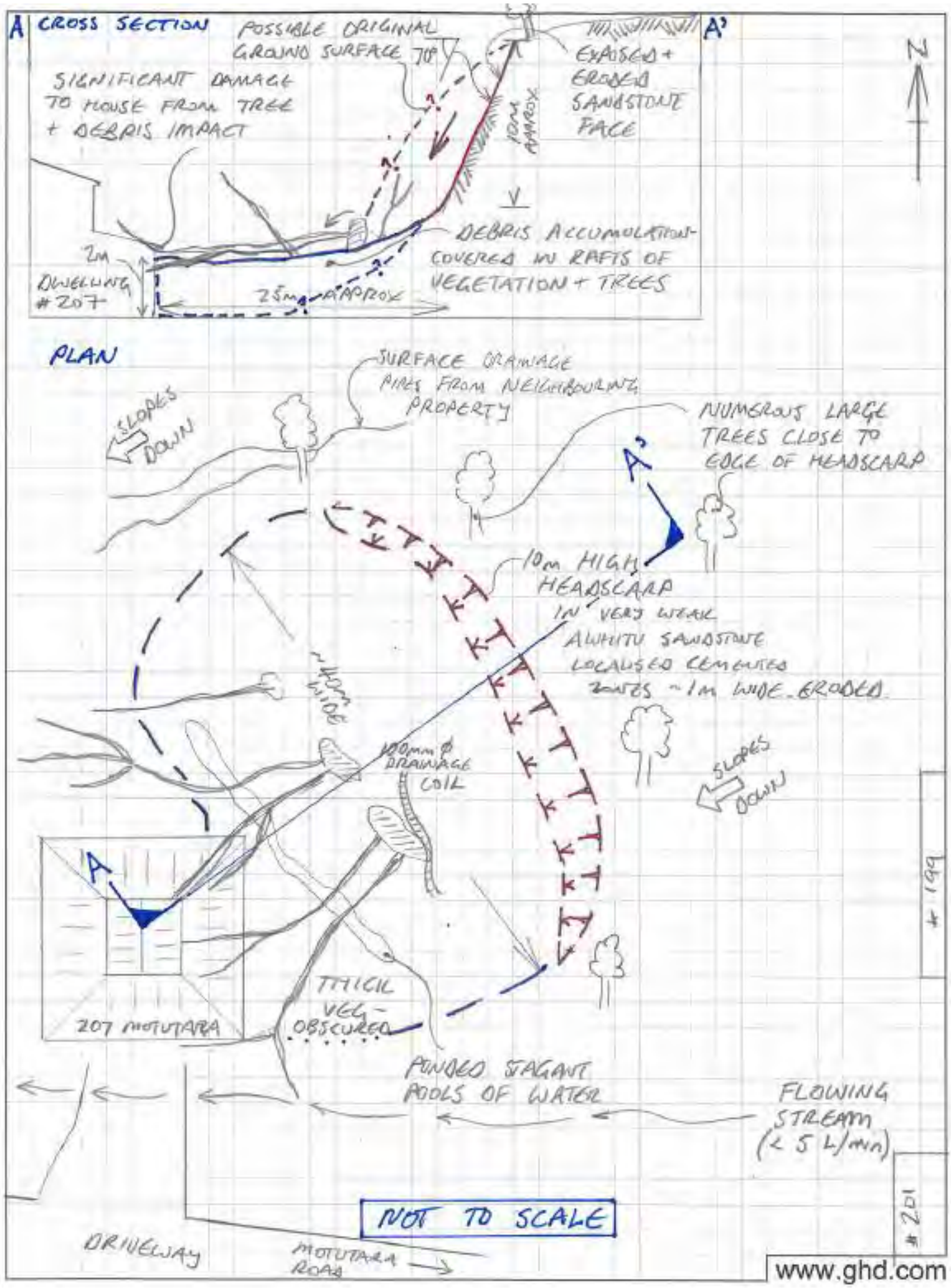


Figure 2.4 *GHD site mapping of the landslide (completed 12 December 2023)*

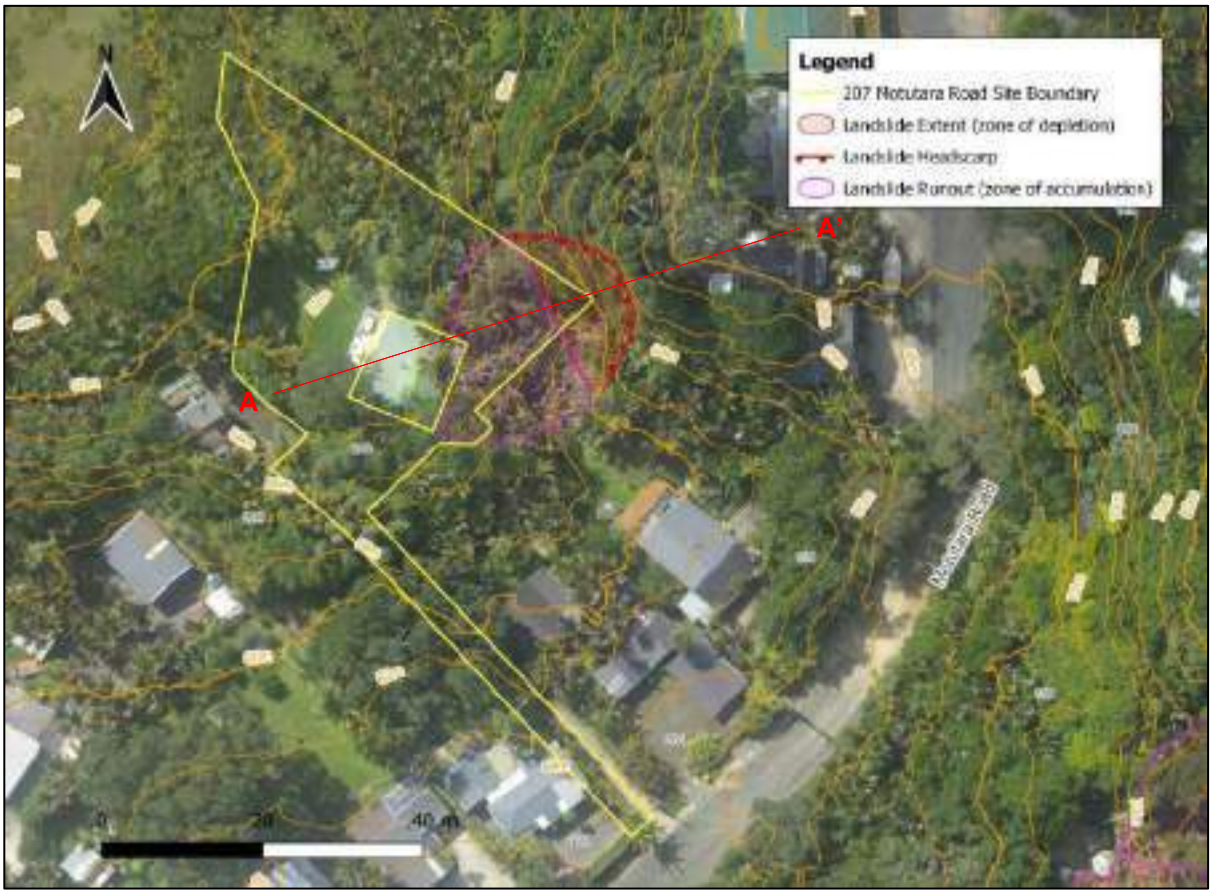


Figure 2.5 **_Landslide location relative to the site shown on February 2023 aerial image._**

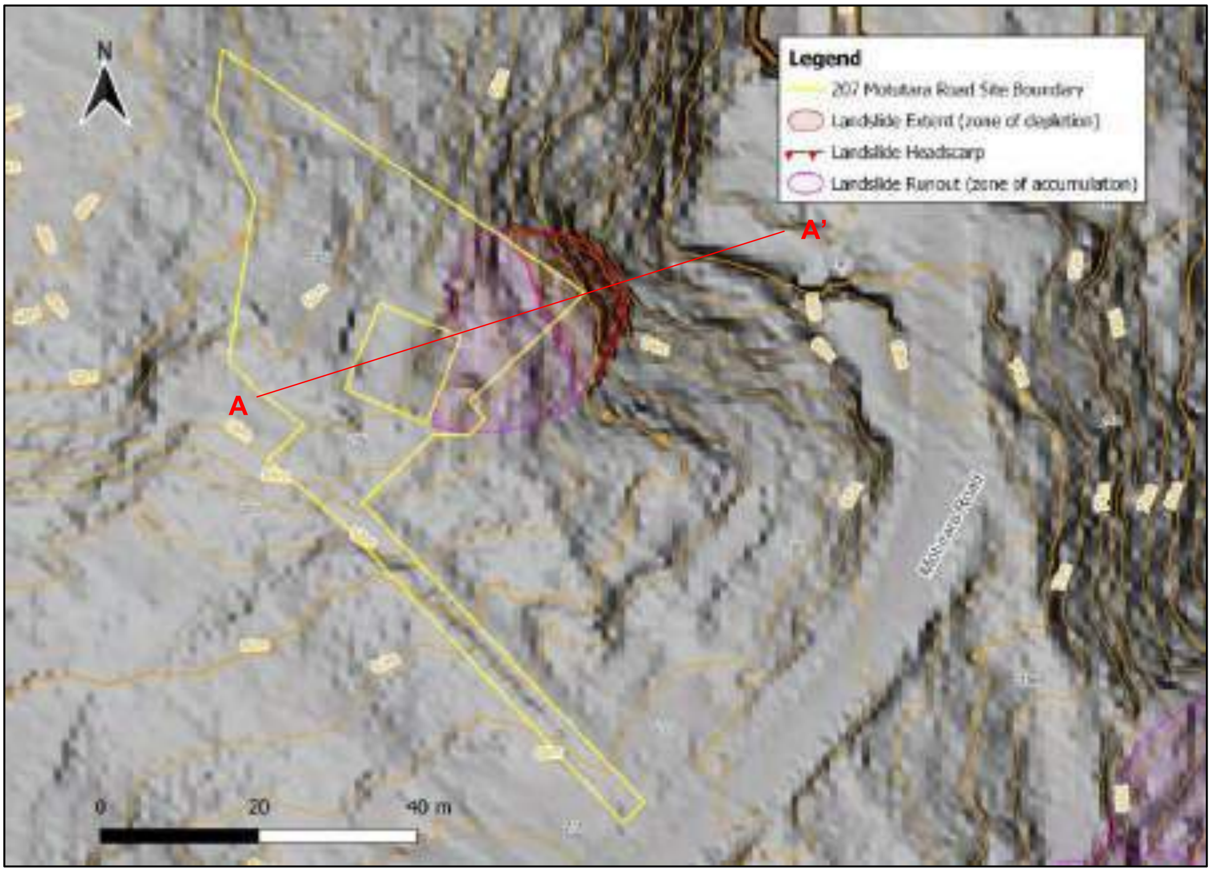


Figure 2.6 **_Landslide location relative to the site shown on LiDAR Hillshade (source: Auckland Council Feb 2023)._**

Figure 2.7 Awhitu Sand Formation in the exposed landslide headscarp.

Figure 2.8 Close to the lateral extent of the landslide debris at the rear of the dwelling, looking southwest.

Figure 2.9 Ponding of water on top of the landslide debris at the rear of the dwelling, looking west.

Figure 2.10 Relatively flat area in front of the dwelling, looking east.

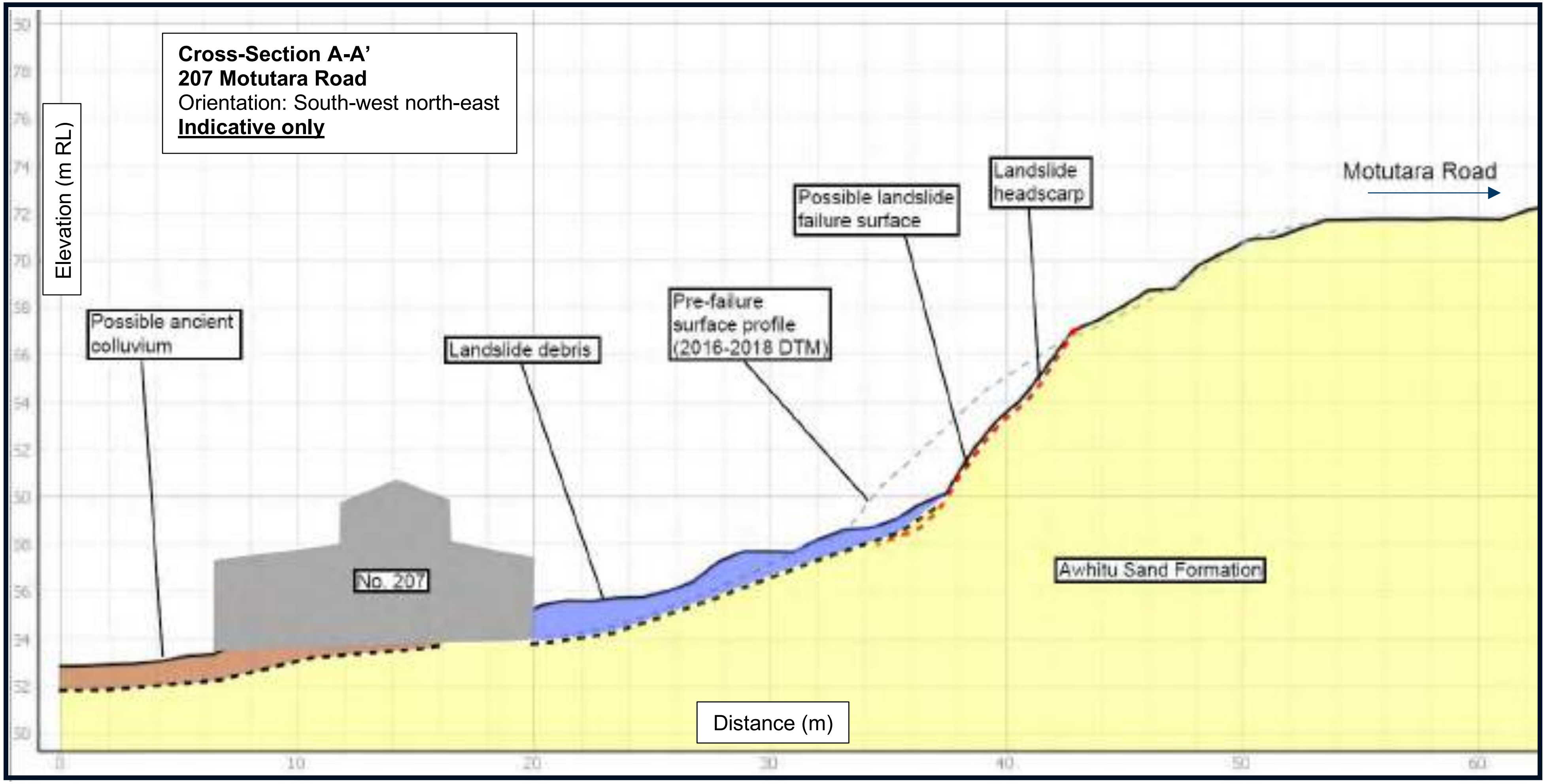


Figure 2.11 ***Indicative interpreted geological cross section through the site at 207 Motutara Road.***

3. Landslide risk estimation

The Australian Geomechanics Society Landslide Risk Management guidelines, published in 2007 and now commonly referred to as AGS (2007), have been adopted for the following unmitigated loss of life landslide risk assessment. Appendix A provides background information and guidance on how the methodology has been applied for assessing risk to life at the site.

The existing dwelling (or a new dwelling of similar construction occupying the same location) has been considered as the element at risk for this assessment. Our assessment assumes the recent landslide debris has been removed. Where appropriate, sensitivity checks have been undertaken for comparative purposes.

3.1 Hazard characterisation

The landslide hazards considered as part of this assessment are as follows:

– **LS1** (Landslide Hazard 1) – The most likely future landslide to occur on the slopes above the property. The landslide would be a shallow failure, likely occurring on the slope along the existing headscarp on the crest of the escarpment and potentially having a volume in the order of 150 m^3. The assumed landslide characteristics have been inferred from observations of the previous failure and landslides to occur elsewhere in Muriwai. The possible source area considered for a future landslide above the dwelling is highlighted on Figure 3.1 and Figure 3.2 below.

– **LS2** (Landslide Hazard 2) – Regression of the existing landslide headscarp. This is likely to have a volume somewhat smaller than the landslide that occurred in February 2023.

3.2 Likelihood of landsliding ($P_{(H)}$)

The basis for estimating probability of occurrence for each landslide hazard considered as part of this assessment is provided in Appendix A and the probabilities adopted are presented below.

3.2.1 Likelihood of LS1

Two considerations of probability for occurrence for the most likely future landslide are:

– $P_{(H'1)}$ is the probability that the rainfall threshold for the most likely significant landslide is exceeded, which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or **0.01** (see analysis by AC in Appendix A) or 1 in 50 or **0.02** under the influence of future climate change.

– $P_{(H'2)}$ is the probability that a slope above the dwellings fails. Given the current condition of the slope above the dwelling, it is conservatively considered almost certain to certain that the most likely future landslide would occur directly above the dwelling. A value of $P_{(H'2)}$ **= 0.5** has been adopted.

3.2.2 Likelihood of LS2

Given the current condition of the exposed landslide headscarp (greater than 45° and comprising Awhitu Sands), it is considered that regression of the existing landslide will occur at the same location during a relatively frequent rainfall event. A value of $P_{(H'1)}$ of **1 in 10** or **0.1** is adopted whilst $P_{(H'2)}$ is considered certain and a value of **1.0** is adopted.

3.3 Probability of spatial impact ($P_{(S:H)}$)

Our estimate of spatial probability is based on several factors which depend on the landslide hazards being considered and site-specific slope conditions. Our approach is detailed in Appendix A. Figure 3.1 and Figure 3.2

below provide an indication of the slope conditions at 207 Motutara Road and the surrounding area (slope angles and inferred preferential flow paths, respectively).

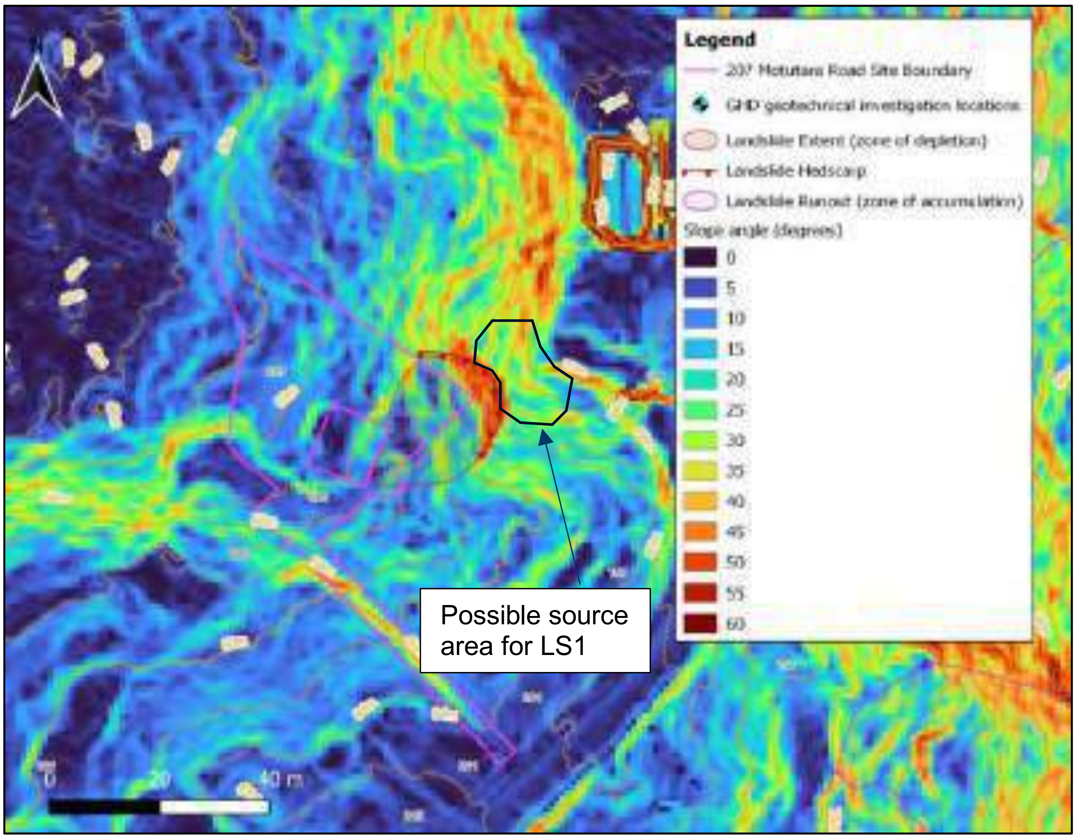


Figure 3.1 ***Slope map of 207 Motutara Road and surrounding area. Slope angles based on 2023 DTM data.***

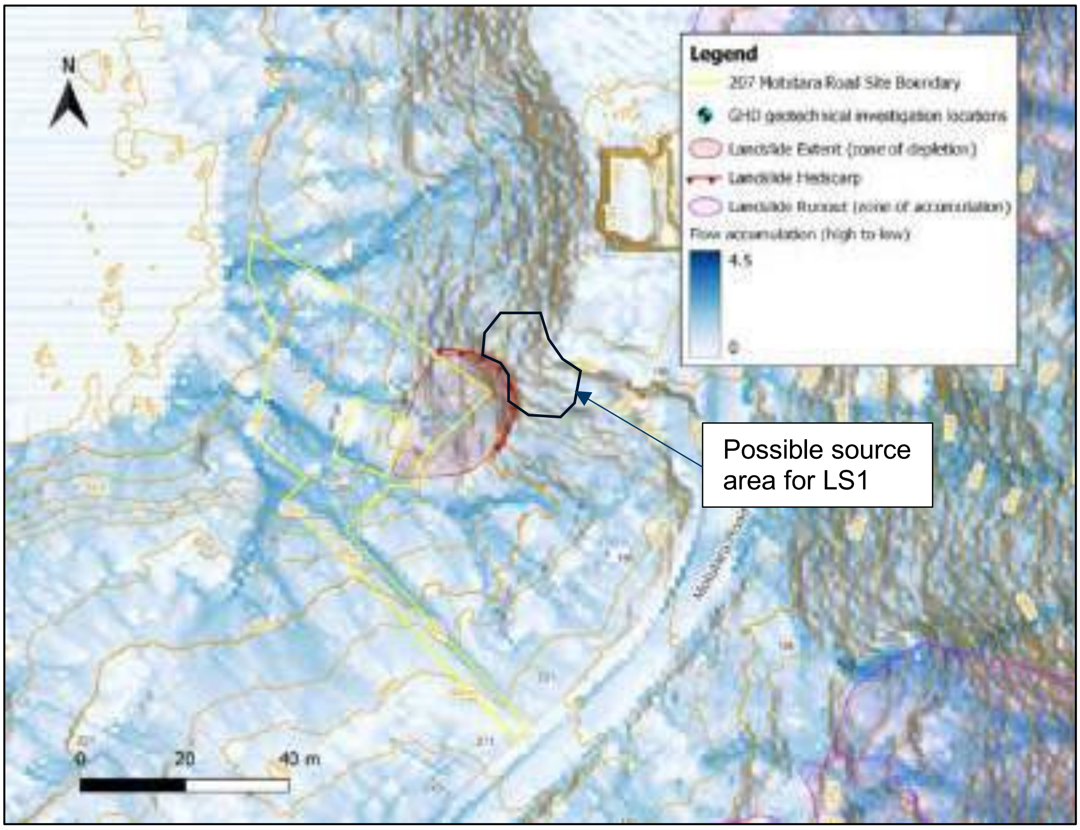


Figure 3.2 ***Flow accumulation map of 207 Motutara Road and surrounding area. Indicates preferential flow path for surface water. Modelling based on 2023 DTM data.***

3.3.1 Probability of spatial impact (LS1)

Two conditional factors are considered for the most likely significant landslide:

– $P_{(S':H'1)}$ is the probability that if the landslide occurs it travels in the direction of (towards) the dwelling. Based on the position of the dwelling at the base of a relatively planar slope exhibiting a somewhat convex geomorphology at its crest, a landslide initiating in the possible source area above the site (Figure 3.1) would likely travel downslope (southwest) towards the dwelling. Based on the flow accumulation plot (Figure 3.2) a landslide is unlikely to take a preferential flow path. A value of **1.0** is adopted.

– $P_{(S':H'2)}$ is the probability that if the landslide occurs it will reach the dwelling. The natural slopes above are generally steep (30-40°). Based on an approximate landslide volume of 150 m^3, an adopted travel angle of 33° (Appendix A methodology based on data from Piha and Karekare) would project the landslide to within 5 m of the rear of the dwelling. Empirical methods in the GHD (2023) Muriwai risk assessment report indicate that, based on an average downslope angle of approximately 35°, the predicted travel distance angle would be approximately 30° (for confined and partly confined travel paths. *Note: LS1 would have an unconfined travel path*). This value also generally agrees with published data in Hunter & Fell (2002). This would project the landslide to the rear of the dwelling. A probability value of **0.5** has been adopted.

3.3.2 Probability of spatial impact (LS2)

Landslide hazard LS2 involves upslope or lateral regression of the existing landslide.

– If the existing landslide hazard were to reactivate and result in regression of the headscarp, it is likely that the new landslide would follow the same path as the previous one, and hence travel towards the rear of the dwelling. As such a probability of **1.0** has been adopted for $P_{(S':H'1)}$.

– Regression of the existing landslide is expected to result in mobilisation of a somewhat smaller volume of debris. Given the observed behaviour of the previous slide (impacting the rear of the dwelling) and the topography of the site, any future failure is judged certain to almost certain to reach the dwelling. As such, a value of **0.8** is adopted for $P_{(S':H'2)}$.

3.4 Temporal spatial probability ($P_{(T:S)}$)

As discussed in Appendix A, a temporal spatial probability of **0.68** is the adopted value for each property and has been used in this assessment.

3.5 Vulnerability ($V_{(D:T)}$)

In the event the future most likely landslide reaches the dwelling from the slopes above, the depth of the debris is likely to be in the order of 1-2 m and result in a similar level of damage as the previous landslide (impact the rear of the dwelling but not result in building collapse or significant inundation). The entrainment of vegetation including large trees has the potential to increase the vulnerability. Therefore, a value **0.05** is adopted for LS1.

In the event that regression of the existing landslide occurs on the slope above the dwelling, it is expected that debris with a somewhat smaller volume than previously would strike the rear of the dwelling but not result in building collapse. Based on the vulnerability table in Appendix A, a value of **0.01** is adopted for LS2.

3.6 Unmitigated Risk Estimation

A summary of the risk estimation for each conceivable landslide hazard is presented in Table 3.1 below. A sensitivity check assuming a higher probability of occurrence for $P_{(H)}$ is included for comparative purposes.

We acknowledge that assessing risk has an inherent degree of uncertainty and may only be accurate to within half an order of magnitude. This level of uncertainty would not change the outcome of the analysis. Refer to Appendix for further discussion.

Table 3.1 Summary of unmitigated risk estimation for each hazard type.

Hazard	Annual probability of the landslide $P_{(H)} = P_{(H'1)} \times P_{(H'2)}$	Spatial probability $P_{(S:H)} = P_{S':H'1)} \times P_{(S':H'2)}$	Temporal probability $P_{(T:S)}$	Vulnerability $V_{(D:T)}$	Risk $R_{(LOL)}$	Risk evaluation*
LS1 ***(most likely future landslide hazard)***	**0.01 x 0.5**	**1.0 x 0.5**	**0.68**	**0.05**	**8.5×10^{-5}**	**Tolerable**
LS1 *Sensitivity check*	*0.02 x 0.5*	*1.0 x 0.5*	*0.68*	*0.05*	*1.7×10^{-4}*	*Not tolerable*
LS2 ***(regression of existing landslide hazard)***	**0.1 x 1.0**	**1.0 x 0.8**	**0.68**	**0.01**	**5.4×10^{-4}**	**Not tolerable**
LS2 *Sensitivity check*	*0.2 x 1.0*	*1.0 x 0.8*	*0.68*	*0.01*	*1.1×10^{-3}*	*Not tolerable*

**The evaluation is a guide only based on recommendations from AGS (2007) which provides a suggested tolerable Loss of Life Risk for the person most at risk.*

4. Conclusion and recommendation

This report has presented the results of a quantitative risk assessment for unmitigated loss of life in relation the property located at 207 Motutara Road, Muriwai, Waitākere. Two landslide hazards (LS1 and LS2) have formed the basis of this assessment.

Assessment of the most likely future landslide (LS1) estimates the annual risk to loss of life for the person most at risk to be approximately **8.5×10^{-5}**. This risk is tolerable based on the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (see Appendix A). Our estimate suggests a higher frequency event as a result of climate change could result in a risk marginally higher than the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk.

Assessment of further (future) failure of the existing landslide hazard (LS2) estimates the annual risk to loss of life for the person most at risk to be approximately **5.4×10^{-4}**. This risk is higher than the AGS (2007c) suggested tolerable Loss of Life Risk for the person most at risk (see Appendix A).

Potential remedial measures to lower the risk level from the existing landslide hazard (LS2) may be possible. However, identifying such measures is outside of the scope of this study.

As discussed above, this report considers geotechnical matters only. There may be other non-geotechnical considerations that affect final placard designation of which GHD are not aware, such as flood risk and structural damage to property.

We understand AC are currently reviewing their tolerable and acceptable risk criteria for risks associated with landsliding. We recommend Council review the risk assessment presented in this report against the AC risk criteria to assess whether it is appropriate to assess the property risk categorisation and remove or re-assess the current placard designation for the site.

5. Limitations

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.

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, 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 assumptions made by GHD described in this report (refer section 1.2 of this report). GHD disclaims liability arising from any of these assumptions being incorrect.

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.

This risk assessment does not mean that there will be no further landsliding impacting this property or group of properties.

Appendix A

AGS (2007) Background

1. Overview

This appendix document outlines the methods and procedures used to estimate risks to loss of life for the person-most-at-risk at the site described in the covering report. This document should be read in conjunction with the covering report as it contains information not presented in the covering report. This document should not be separated from the main report.

2. Landslide Risk Management Framework

2.1 Background

The 1998 Thredbo landslide, in which 18 persons were killed, highlighted the challenges faced from building upon steep slopes and led to the development of the Australian Geomechanics Society Landslide Risk Management guidelines, published in 2007 and now commonly referred to as AGS (2007). The suite of guidelines is recognised nationally (Australia) and internationally as world-leading practice. The reader of this report is encouraged to consult the freely available LRM resources which can be accessed at: https://landsliderisk.org/.

The ”Practice Note Guidelines for Landslide Risk Management” (AGS 2007c), provide technical guidance in relation to the processes and tasks undertaken by geotechnical practitioners who prepare LRM reports including appropriate methods and techniques. The Practice Note is a statement of what constitutes good practice by a competent practitioner for LRM, including defensible and up to date methodologies and provides guidance on the quality of assessment and reporting, including the outcomes to be achieved and how they are to be achieved.

The framework for landslide risk management is presented in the figure below and represents a framework widely used internationally.

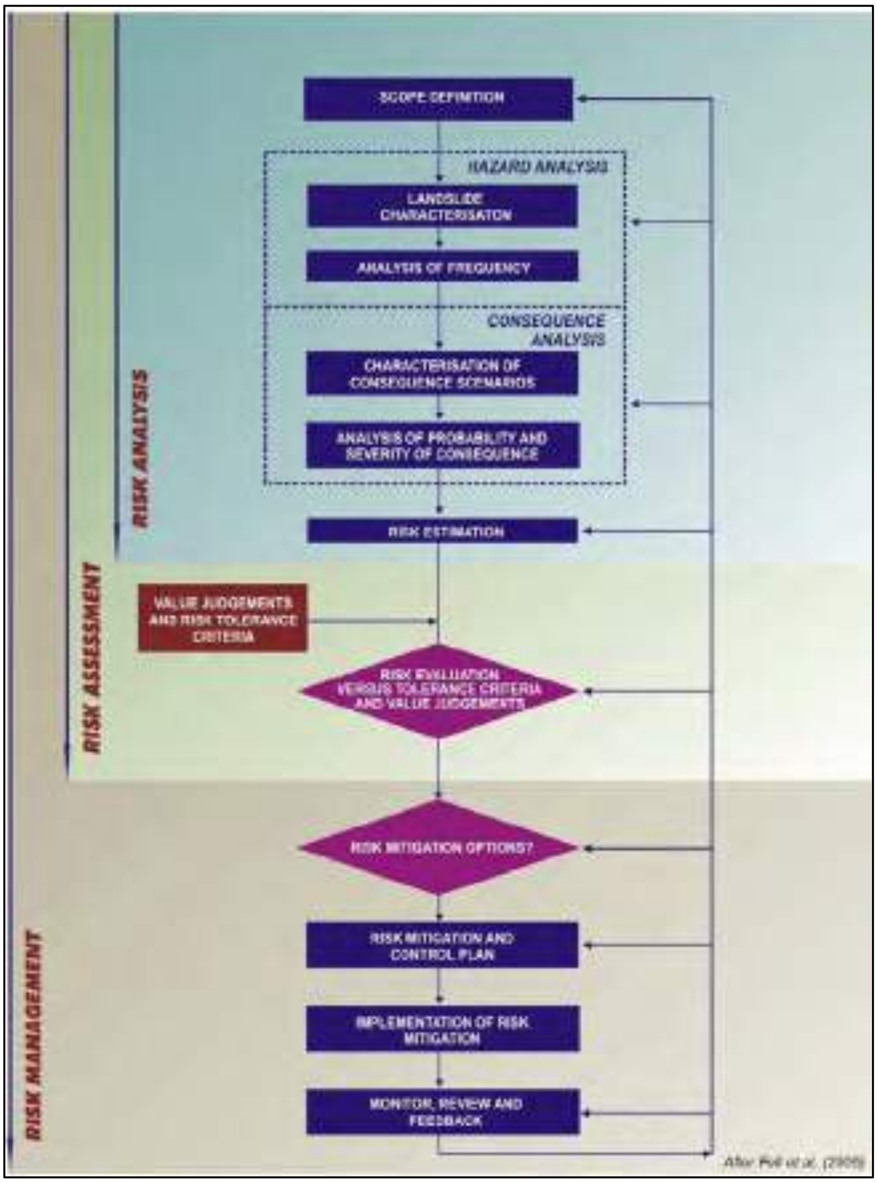


Figure A1 *Framework for landslide risk management.*

2.2 Risk Estimation Methodology

AGS (2007c) requires risks to loss of life to be estimated quantitatively for the person-most-at-risk. The person-most-at-risk will often but not always be the person with the greatest spatial temporal probability (i.e. the person most exposed to the risk). The Individual Risk-to-Life is defined as the risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide; or who follows a particular pattern of life that might subject him or her to the consequences of the landslide. The risk of 'loss-of-life' to an individual is calculated from:

$$\mathbf{R}_{(LoL)} = \mathbf{P}_{(H)} \times \mathbf{P}_{(S:H)} \times \mathbf{P}_{(T:S)} \times \mathbf{V}_{(D:T)}$$

Where:

$\mathbf{R}_{(LoL)}$ is the risk (annual probability of death of an individual).

$\mathbf{P}_{(H)}$ is the annual probability of the landslide (event).

$\mathbf{P}_{(S:H)}$ is the probability of spatial impact of the event impacting an individual taking into account the travel distance and travel direction given the event. For example, the probability of an individual in a building or in the open being impacted by a rockfall / landslide at a given location.

P$_{(T:S)}$ is the temporal spatial probability (e.g. of the building or location being occupied by the individual at the time of impact) given the spatial impact and allowing for the possibility of evacuation given there is warning of the event occurrence.

V$_{(D:T)}$ is the vulnerability of the individual (probability of loss of life of the individual given the impact).

2.3 Landslide Risk Assessment Uncertainty

The process of risk assessment involves estimation of likelihood, consequence and risks based on available information for the study site. By its very nature, much of the data, including historical and current inventories may be incomplete whilst an understanding of the triggering events has a degree of uncertainty attached to it. Judgement is required to estimate the nature and size of potential hazards, their frequency of occurrence and their impact on a variety of elements at risk. As these judgements are based on the knowledge, experience and understanding of the assessor, it is not unusual for different assessors to make different judgements about the level of risk.

The thought process used in establishing likelihoods, consequences and determining spatial and temporal factors for properties has been documented for transparency. The structure of the risk assessment process is well defined and values for some input parameters have been tabulated to guide standard approaches by different assessors. However, this should not be mistaken for precision given the limitations of the inputs outlined above. Generally, the levels of likelihoods and risks should be thought of as being within a range of typically +/- half an order of magnitude.

While the basis for the judgements contained in this report are well documented, and the levels of risk considered to be good representations of reality, the accuracy and precision of the process should not be overestimated and should always be used in an appropriate manner in combination with risk management including mitigation and treatment options.

3. Hazard Characterisation

AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This is generally a predictive exercise based on knowledge and understanding of the geological and geomorphological setting with a view to assembling historical evidence for past hazard events.

3.1 Defining the Most Likely Significant Landslide

Following Cyclone Gabrielle, small landslides within the Muriwai area were often noted to be shallow translational slides developed in the upper residual profile of the Awhitu Sand Formation which, under saturation, transition into debris flows. Detailed analysis by GHD of the mapped landslides within the Karekare and Piha areas, which included size, estimated volume, travel distance and travel angle, was undertaken to characterise the nature and distribution of landslides following the rainfall events that occurred in early 2023, particularly the Cyclone Gabrielle rainfall event, has been used as a basis for defining the magnitude of the ‘most significant landslide’ for the site.

A total of 80 landslides were mapped throughout Karekare and Piha following the storm events in Jan and Feb 2023. These landslides were then grouped into categories of volume in 50 m^3 increments. Results for an assessment of “frequency as categorised by volume” is shown in Figure 1 below.

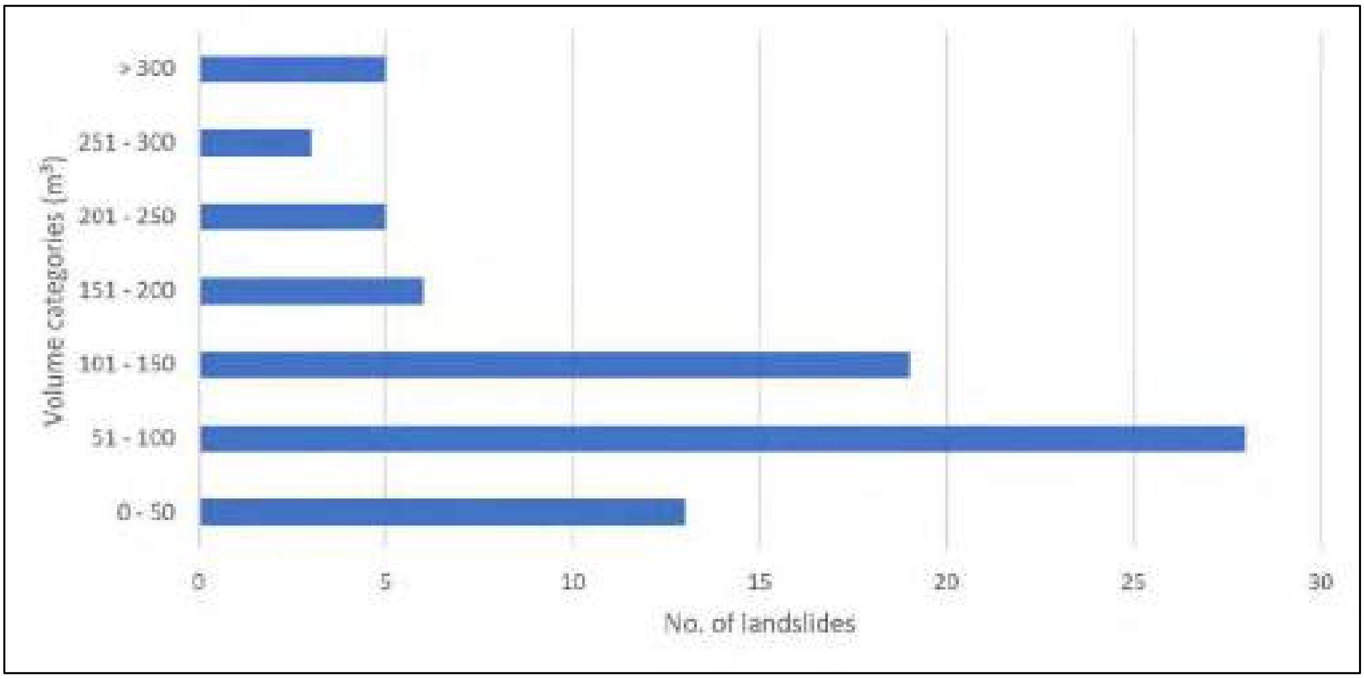


Figure A2 ***The number or frequency of mapped debris flows (on the x axis) as categorised by volume increments for mapped source areas of debris flows (on the y axis in m^3) in Karekare and Piha.***

In addition, detailed information regarding volume size, travel angle, travel distance, confinement (either unconfined or channelized) and the degree of damage caused by slides impacting dwellings and building was also collated and a number of additional graphs were developed as below:

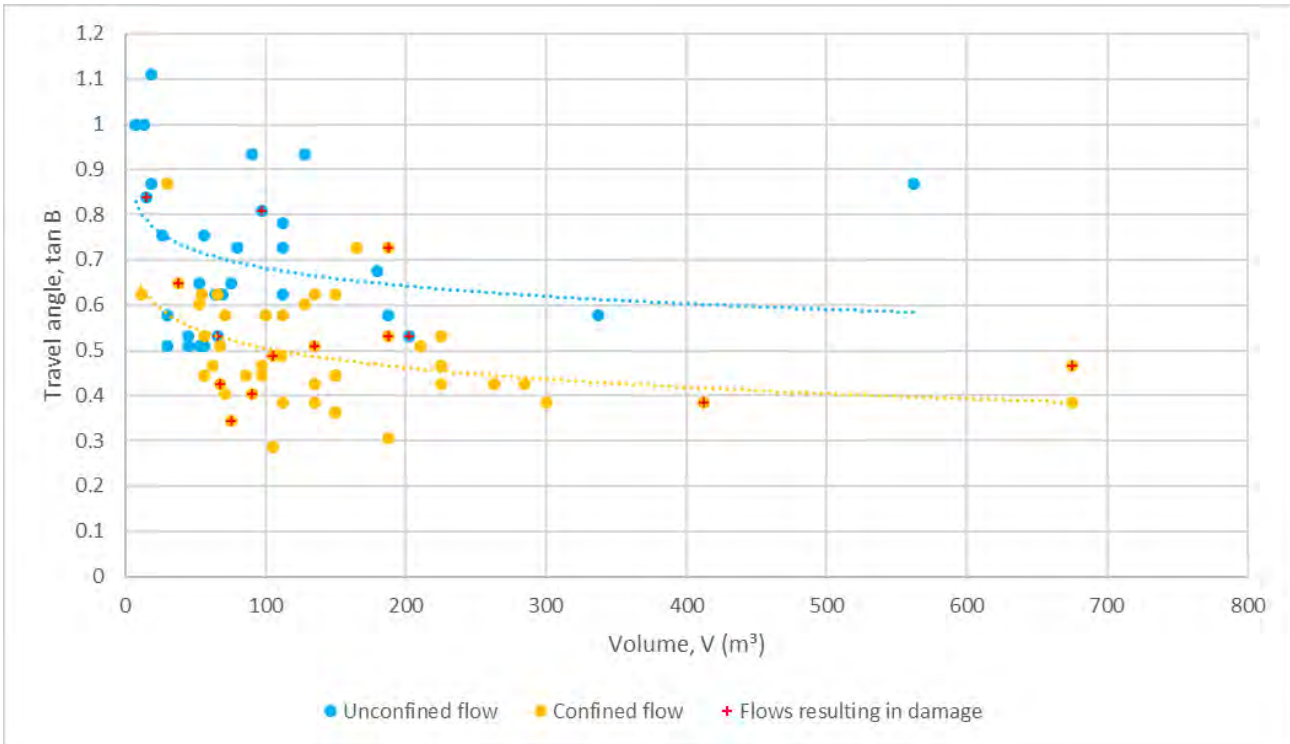


Figure A3 ***Travel angle vs volume of source area for the Karekare and Piha debris flows***

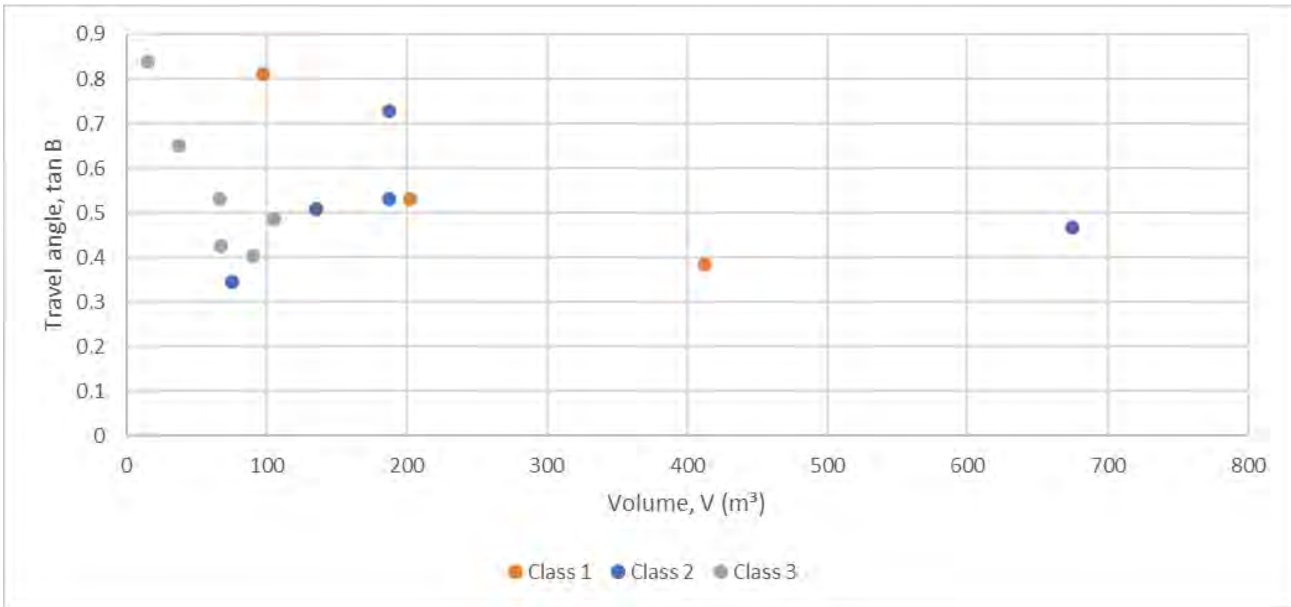


Figure A4 ***Plot of only those debris flows known to have caused some degree of damage to dwellings and buildings. Note Class 1 = Complete destruction/collapse of building, Class 2 = Partial destruction/collapse of building, significant inundation and Class 3 = Limited damage to building but no collapse or inundation, damage is other property infrastructure e.g., access stairs.***

This assessment highlights a number of important points relating the nature of these hazards including:

– Whilst a range of volumes of source areas for debris flow was noted, the most common or likely sized event was of the order of 50-100 m^3 as determined by the frequency plot.

– Many smaller volume source areas for debris flows (less than 75 m^3) typically only caused some lesser damage to buildings but once the volume increased above 100 m^3, then the vast majority of debris flows were noted to have caused partial or full collapse of dwellings and buildings.

– The greater the volume of the source area, the lower the travel angle and the greater the runout or travel distance.

– Unconfined debris flows generally have a higher travel angle compared to confined or channelized debris flows of the same volume. This means that confined or channelised debris flows have a longer runout or travel distance and hence have more potential to impact elements at risk further down the slope.

Based on this site-specific data and analysis, GHD has adopted a working definition for these risk assessments of what is termed the **most likely significant landslide** as follows:

– The volume of most likely significant landslides is assumed to be 100 $m^{3.}$

– This volume has been shown to cause significant building damage resulting in partial to full dwelling and building collapse.

– As a result, this hazard is considered to have a high probability for causing loss of life.

– Where this hazard is unconfined, the adopted travel angle based on Figure 3 has been taken as Tan (B) = 0.69 or approx. = 35°

– Where this hazard is confined or channelised the adopted travel angle based on Figure 3 has been taken as Tan (B) = 0.50 or approx. = 26.5°

– Comparison with Figure 6 from Hunter and Fell (2002) suggests the site derived travel angles are generally consistent with other data presented in that plot.

The definition of the **most likely significant landslide** is considered to be a reasonably conservative but not overly cautious estimate of the potential hazard that may affect the site. This is based on an assessment of an overview of landslides that GHD has observed in Muriwai, Karekare and Piha in 2023.

It is noted however that in some specific circumstances, larger recent debris flows may have occurred in close proximity to the site under investigation. As such, where there is evidence for a larger hazard, the assessor may

choose to adopt a larger volume event based on judgement and knowledge of that particular site. In this case other values for travel angle can be read from Figure 3.

IMPORTANT NOTE: It is duly acknowledged that volume alone does not necessarily account for the full potential of a debris flow to cause significant damage and other factors such as the degree of channelization, the additional entrainment of volume within a channel, the degree of saturation of the debris materials, the location of the source area on the hillslope, the direction of travel, the distance of travel and the velocity of the hazard at the point of impact all play important roles in the destructive capacity of any debris flow. Some of these factors are considered within the risk assessment process as conditional probabilities in spatial considerations.

3.2 Description of Other Landslide Types

As discussed in the scope of the covering report, other landslide hazards may exist at the site under assessment. These may include existing geohazards that have resulted from recent failures with the potential to pose risk to life in the immediate short-term (i.e. within the next few years) such as regression of translational failures to occur downslope of dwelling, failure of over-steepened fill and cut slopes, rockfall hazards associated with exposed rock faces/headscarps and/or loose debris remaining upslope of dwellings.

In addition, other possible geotechnical slope instability hazards relating to modified slopes (i.e. human made) may also exist and have potential to pose a risk to life - such as failures of fills, cuttings and failed retaining walls. This represents hazards that may have a range of likelihood from almost certain to possible.

Where appropriate, descriptions and definitions for each of these hazards are provided in the covering report on a case-by-case basis and will be specific to the observed hazard and actual conditions at this site.

3.3 General Descriptors for Size Classification of Landslides.

Generalized or relative descriptions of size classification systems for landslides vary significantly depending on the country of origin and the nature of the landslide hazards typically encountered. For the purposes of these assessments, GHD proposes to use the following size classification descriptions adopted from the Transport for New South Wales (TfNSW) Guide to Slope Risk Analysis Version 4 (TfNSW 2014) (see Table 3.1 below).

Table A3.1 Landslide size classification

Relative size term	Volume range	Typical mid-range dimensions (width x length x depth in metres)
Very small	<20 m3	4 x 4 x 0.5
Small	20 to 200 m3	10 x 10 x1
Medium	200 to 2000 m3	20 x 20 x 2.5
Large	2000 to 20000 m3	40 x 40 x 5
Very large	>20,000 m3	60 x 60 x 8

4. Likelihood $P_{(H)}$

Likelihood or annual probability of occurrence of the landslide, $P_{(H)}$, is one of the most critical but difficult to estimate factors as part of the risk assessment process.

4.1 The Most Likely Significant Landslide

The recent flood / storm events, the estimation of recurrence intervals for that event and the occurrence of the observed hazards form the basis for the current estimated probability of occurrence for the most likely significant landslide hazard. However, observations of the recent events noted that not all similar slopes failed as a result of

the initiating storm event and as such, an additional consideration for probability of occurrence has been included within the analysis by using conditional probabilities as follows:

$$P_{(H)} = P_{(H'1)} \times P_{(H'2)}$$

Where:

$P_{(H'1)}$ = Probability that the rainfall threshold for the most credible significant landslide is exceeded which is taken as a proxy for landslide initiation. This is assumed to be 1 in 100 or 0.01 (see analysis and discussion by Auckland Council below) or 1 in 50 or 0.02 under the influence of future climate change.

$P_{(H'2)}$ =Probability that the slope for the specific assessment fails, which relates to how many of the actual slopes failed out of the total number of all slopes present. This probability is typically based a on spatial analysis of the total area of failed landslides slopes compared to the total area of all slopes for the geomorphic setting in which the site is located.

4.2 Auckland Council Guidance on Frequency for Most Likely Significant Landslide

Council provided GHD with an assessment of available rainfall data associated with Cyclone Gabrielle (Auckland Council 2023) (AC memo). During Cyclone Gabrielle, the tipping bucket rain gauge at Muriwai failed and was inundated by flood waters. The AC memo also provided rainfall analysis using AC's Quantitative Precipitation Estimate (QPE) Rain Radar System, which is a real-time rainfall product that utilises the MetService radar. The rainfall data presented by AC indicates a peak rainfall total for Muriwai during the event of 146.9mm, 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 as a result of the relatively short statistical rainfall records available in New Zealand. For the other durations modelled, the rainfall was below the 100-year event.

The AC memo recommended that an envelope of "risk" is estimated as the ARI figures will change over time and as these events are incorporated into the statistical record. The AC memo states that in general, it is considered reasonable to consider the Cyclone Gabrielle event to be in the range of 100-250 year ARI. For this assessment we have assumed that the annual likelihood of a landslide event occurring that is similar in magnitude to the February 2023 event, is about 1 in 100 (i.e., 0.01). This is considered to have a *likely* probability of occurrence.

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 are difficult to quantify.

The AC memo further recommended that risk assessment reports consider the potential for climate change to increase the frequency of high intensity rainfall. We understand that the National Institute of Water and Atmospheric Research (NIWA) has projected a 20% increase in rainfall intensity over the next 100 years which suggests that a 250-year ARI event could increase to a 50-year ARI event. Consequently, we have also included a sensitivity check based on a 50-year ARI event.

We draw the reader's attention to Section 3 of this report and reiterate that AGS (2007c) generally states that all credible hazards originating on, above and below the sites should be assessed. This report has conformed to this requirement and assessed landslide hazards that were observable during the site mapping and/or able to be interpreted via other means such as readily available aerial photographs, lidar data etc. It should be recognised that specific hazards such as rockfalls, failed retaining walls, over-steepened cuts/fill batters may have likelihoods in the *Certain to Almost Certain* range and are more likely to occur in the short term.

4.3 Other Landslide Hazards

Where other slope failures and instabilities as described in Section 3.2 are considered, individual assessments of $P_{(H)}$, the probability of occurrence, are made on the basis of expert judgment, performance of similar landslides in the area and recent site observations.

When considering hazards that may pose immediate or short-term risks to life it is probable that such hazards will have high likelihoods of occurrence that could be triggered by relatively frequent events. As a result, such hazard may have likelihoods in the *Certain to Almost Certain* range as per the ASGS2007 qualitative descriptors for likelihood.

5. Probability of Spatial Impact $P_{(S:H)}$

The AGS definition of spatial probability is represented by single term $P_{(S:H)}$ and is described as the probability of spatial impact by the landslide on the element at risk, given the landslide occurs and taking into account the travel distance and travel direction.

5.1 The Most Likely Significant Landslide - Upslope of Site

A number of conditional factors may be involved in the spatial distribution for the most likely significant landslide, and for further transparency, the following methodology has been adopted:

$$P_{(S:H)} = P_{(S':H'1)} \times P_{(S':H'2)}$$

Where:

– $P_{(S':H'1)}$ = The probability that if the landslide occurs it travels in the direction of the site under assessment. If the slopes above are consistent, and planar then probability is assumed to be 0.8 to 1.0 depending on the topography; if the originating landslide enters a channel that is directed onto the property then probability is assumed to be 1.0, or if the landslide enters a channel that is directed away from the sites then the probability is assumed to be 0.05 taking account of a small probability that the landslide may super elevate and leave the channel.

– $P_{(S':H'2)}$ = The Probability that if the landslide occurs it will travel to at least the site under assessment and will impact the property. This is to be based on two considerations as follows:

1. Modelled Behaviour based on travel distance analysis undertaken by GHD for 80 observed landslides slides in the Karekare and Piha areas (see Figure A3). Either probability = 1.0 if the travel angle projects past the dwelling, = 0.5 if the travel angle projects to the rear of the dwelling or = 0.0 if the travel angle falls short of the dwelling.

And/or

2. Observational behaviour: based on site observations of whether the previous landslides within close proximity to the study site, travelled sufficient distance to reach the site under assessment; if yes Probability = 1.0, if no, then probability = 0

– NOTE 1: The GHD analysis of travel distance highlights the effect of channelisation which shows confined debris flows travel further (i.e., they have a lower travel angle) than those which are unconfined on consistent or planar slopes. Such considerations are included on a site-by-site basis. Interestingly, this event-specific analysis also generally agrees with findings presented in Hunter and Fell (2002).

– NOTE 2: Where significant debris flows have occurred in close proximity to the site under assessment, and the observed travel distance is greater than that estimated using the modelled approach, the preferred GHD approach is to use the greater of the two travel distances to assess spatial impact.

5.2 The Most Likely Significant Landslide – Under the Dwelling/Building and/or Downslope Below the Dwelling/Building

Based on the possible failure area:

- If the failure area is > ~5 m from the dwelling then the value for $P_{(S:H)}$ will be 0 as a landslide occurring at that location will not impact dwelling. (The general assumption is that the landslide headscarp would have a length of 5m based on size of most likely significant landslide).
- If the failure area is within ~5m from the dwelling (like above) then the value for $P_{(S:H)}$ will be 0.5 to account for uncertainty of it encroaching within the footprint of the dwelling.
- If the failure area encompasses a significant portion of the dwelling then the value for $P_{(S:H)}$ will be 1.0 as there is a certain probability it will impact the dwelling.

Estimates of how far back the most significant landslide will regress are difficult to model without a detailed slope stability analysis and sufficiently accurate soil and rock inputs. This would require an intrusive geotechnical investigation which is outside the scope of this study.

GHD has adopted a more empirical approach that assesses the spatial extent of lateral downslope movement of the most likely significant landslide based on direct observations of existing landslides in close proximity to the site under assessment. In the absence of other information, a similar extent of regression has been applied to any future slides. An estimate of $P_{(S:H)}$ can then be made as to the potential interaction with the element at risk.

5.3 Other landslides – Upslope of the study site

Other types of potential landslides situated above dwellings and buildings on the site under assessment, should be assessed in a similar manner to the most likely significant landslide. Estimates of travel distance are taken from Hunter and Fell (2002) and/or previous local knowledge and/or observation of similar landslides in the area.

When undertaking short term assessments, hazards involving reactivation of existing landslides that are located upslope of the study site that didn't previously reach the site must be taken account. In addition, remobilisation of debris from any upslope landslides must also be assessed for their potential of runout or travel distance using Hunter and Fell (2002).

Similarly potential failures of modified slopes such as cuttings or fills located above or directly adjacent to dwellings and buildings must also be assessed for their spatial impact and the methods of assessment follow the same approach.

5.4 Other landslides – under buildings and downslope of the building

A similar approach to that taken for other landslides upslope has been adopted. Observation of existing failures and how much lateral downslope movement can be used as a proxy for what may occur in the future under a regression type scenario.

5.5 Temporal Spatial Probability $P_{(T:H)}$

These risk assessments have not considered specific occupancy scenarios for each individual residence. We acknowledge that the occupancy of each residence could vary significantly depending on the demographics of the residents and the usage of the residence. For example, some residences may be predominantly used as holiday accommodation, occupied mainly on weekends, whereas other residences could be permanently occupied by working families.

This assessment has assumed the following occupancies:

– Residences are typically occupied for 15 hours each day during weekdays;
– On weekends, residences are occupied for about 20 hours each day;

– The percentage of time a residence is occupied is therefore about 68%.

Any further delineation of the spatial variations in occupancy (i.e. if a bedroom is at the front or the rear of the house etc) are not considered feasible or warranted within the context of the precision of this assessment.

6. Vulnerability $V_{(D:T)}$

6.1 Most likely significant Landslide

AGS (2007c) includes a table of vulnerability values for various inundation and building damage scenarios as adapted by Finlay et al (1999). It is important to note that the AGS (2007c) vulnerability table doesn't adequately cater for all the building damage scenarios GHD has observed in Muriwai, Karekare and Piha. GHD has therefore further adapted this table and combined it with information from the TfNSW Guide to Slope Risk Analysis (2014) as well as observations of damage to buildings and structures resulting from the recent landslides in Muriwai, Karekare and Piha.

The table of vulnerability values used in this assessment is presented in Table A6.1. These values have been used as a guide and expert judgement has been applied to select a value within the range of values where appropriate on a site-specific basis.

Table A6.1 Summary of Vulnerability Values adopted

Case	Range	Typical value to be used in this assessment	Comments
Person in a building that collapses under impact from debris flow	0.8 -1.0	0.9	Death is almost certain. Evacuation unlikely to occur
If building is inundated with debris and the person is buried	0.8 -1.0	0.8	Very high potential for death Evacuation unlikely to occur
If building is inundated with debris but no collapse occurs and the person is not buried	0.01 -0.1	0.1	High chance of survival Evacuation unlikely to occur
If the debris strikes the building only	0.001-0.05	0.01	Very high chance of survival
If failure occurs below the building and results in significant collapse	0.5-0.8	0.6	Moderate to high potential for death. No forewarning signs with evacuation unlikely to occur.
If failure occurs below the building and results in partial collapse	0.01 -0.1	0.05	High chance of survival. Signs of building distress should provide occupants with opportunity to take evasive action.
If failure occurs below the building and results in damage. No collapse occurs.	0.001-0.05	0.005	Very high chance of survival. Evacuation almost certain.

7. Risk Evaluation

The main objectives of risk evaluation are usually to compare the assessed risk to risk levels that are acceptable or tolerable to the community, and therefore to decide whether to accept, tolerate or treat the risks and to set

priorities for remediation. The Tolerable Risk Criteria are usually imposed by the regulator, unless agreed otherwise with the owner/client. AGS (2007d) provides discussion and gives the AGS recommendations in relation to tolerable risk for loss of life. These are summarized in the table below.

Table A7.1 AGS Suggested Tolerable loss of life individual risk.

Situation	Suggested Tolerable Loss of Life Risk for the person most at risk
Existing Slope / Existing Development	10^{-4} per annum (1E-4 pa) or 1 in 10,000 pa
New Constructed Slope / New Development / Existing Landslide	10^{-5} per annum (1E-5 pa) or 1 in 100,000 pa

It is important to distinguish between "acceptable risks" and "tolerable risks". AGS (2007c) states that tolerable risks are risks within a range that society can live with so as to secure certain benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if practicable. Acceptable risks are risks which everyone affected is prepared to accept. Acceptable risks are usually considered to be one order of magnitude lower than the Tolerable risks.

8. References

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.

Australian Geomechanics Vol 42 No 1 March 2007 Extract "Practice Note Guidelines for Landslide Risk Management 200" AGS (2007c)

P J Finlay, G R Mostyn & R Fell (1999). 'Landslides: Prediction of Travel Distance and Guidelines for Vulnerability of Persons'. Proc 8th. Australia New Zealand Conference on Geomechanics, Hobart. Australian Geomechanics Society, ISBN 1 86445 0029, Vol 1, pp.105-113.

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

New South Wales Government, Transport for New South Wales 'Guide to Slope Risk Analysis' Version 4, April 2014.

Appendix B

Glossary of Terms

DEFINITION OF TERMS

Acceptable Risk – A risk which, for the purposes of life or work, society is prepared to accept as it is with no regard to its management. Society does not generally consider expenditure in further reducing such risks justifiable.

Authority or **Council** having statutory responsibility for community activities, community safety and development approval or management of development within its defined area/region

Consequence – The outcomes or potential outcomes arising from the occurrence of a landslide expressed qualitatively or quantitatively, in terms of loss, disadvantage or gain, damage, injury or loss of life.

Creep Failure – A time-dependant deformation mechanism where constant stress is applied to a material. Creep failure can be identified by ridges the ground surface and curved tree trunks.

Dropout – A landslide feature occurring along the length of the road-side on the downslope edge. Drop outs can result in the undermining the road carriageway.

Elements at Risk – The population, buildings and engineering works, economic activities, public services utilities, infrastructure and environmental features in the area potentially affected by landslides.

Entrainment – The process of surface sediment transportation through water and mass movement.

Frequency – A measure of likelihood expressed as the number of occurrences of an event in a given time. See also Likelihood and Probability of Occurrence.

Hazard – A condition with the potential for causing an undesirable consequence. The description of landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached material, and the probability of their occurrence within a given period of time.

Individual Risk to Life – The risk of fatality or injury to any identifiable (named) individual who lives within the zone impacted by the landslide or who follows a particular pattern of life that might subject him or her to the consequences of the landslide.

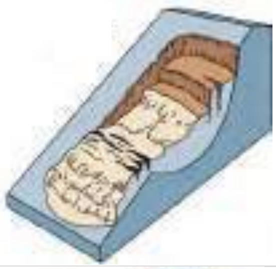
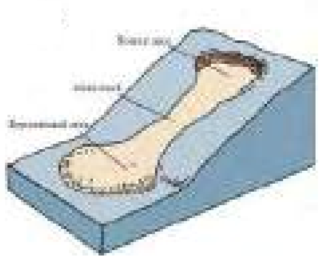
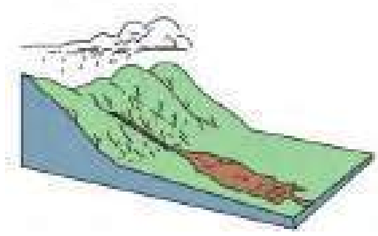
Landslide - A landslide is defined as the movement of a mass of rock, debris, or earth down a slope. The most widely used landslide classification system is that proposed by Cruden and Varnes in 1996 (after Varnes 1954 and Varnes 1978). This has been updated by Hungr, et al., 2014. In its most simple form two nouns are used to describe, firstly the type of material involved and secondly, the mechanism of failure, i.e., rock fall, debris flow.

Landslide inventory – An inventory of the location, classification, volume, activity and date of occurrence of landsliding

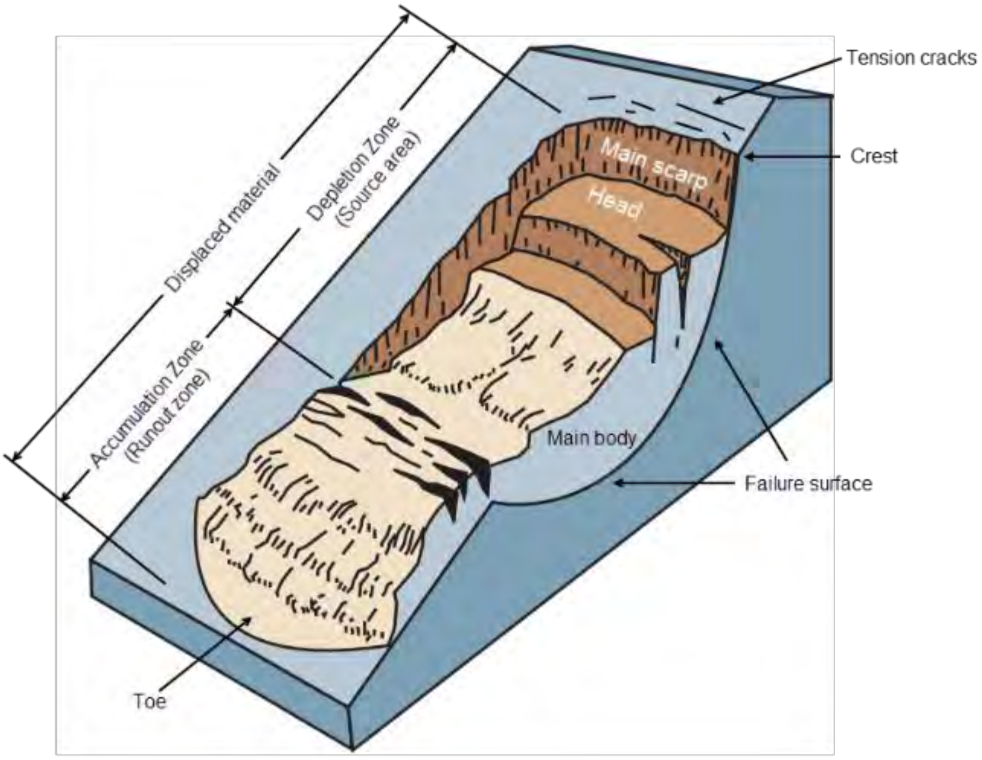
Landslide Risk - Landslide risk is defined herein as the likelihood that a particular landslide will occur and the possible consequences to a specific element at risk (property or human life) taking account of both spatial and temporal considerations.

Landslide Susceptibility – A quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding.

Landslide Classification – Referenced from Varnes, 1978.

Landslide Type	Landslide Description	Illustration
Rotational sliding	The landslide failure surface is curved concavely upward and the movement of mass is mainly rotational. Rotational movement causes back tilting of the displaced material near the headscarp.	
Translational sliding	The landslide mass moves along a planar failure surface with minor rotational movement.	
Earth flow	The movement of saturated fine-grained materials or clay bearing rocks. The displaced material forms a characteristic hourglass shape with an elongated flow path.	
Debris flow	The rapid movement of saturated, loose material caused by heavy precipitation and surface water flow. Commonly occurring on steep slopes.	
Debris avalanche	A type of debris flow that is *extremely* rapid.	
Rock fall	The separation of rocks and boulders along fractures, joints and bedding planes on steep slopes or cliffs. The movement is heavily influenced by mechanical weathering of the rock mass and gravity.	

Landslide characteristics – Modified after Varnes, 1978.



Likelihood – Used as a qualitative description of probability or frequency of the event/landslide.

Overland Flow Path – The predicated flow path of stormwater over the topography.

Permeability – The capacity of a material to allow water to pass through it. Clay materials are impermeable whereas gravels and sands are porous and therefore permeable.

Probability – A measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the likelihood of the magnitude of the uncertain quantity or the likelihood of the occurrence of the uncertain future event. There are two main interpretations:

(i) Statistical – frequency or fraction – The outcome of a repetitive experiment of some kind like flipping coins. It also includes the idea of population variability. Such a number is called an "objective" or relative frequentist probability because it exists in the real world and is in principle measurable by doing the experiment.
(ii) Subjective probability (degree of belief) – Quantified measure of belief, judgement, or confidence in the likelihood of a outcome, obtained by considering all available information honestly, fairly and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation or the quality and quantity of information. It may change over time as the state of knowledge changes.

Probability of Occurrence – used interchangeably with Likelihood.

Quantitative Risk Analysis – an analysis based on numerical values of the probability, vulnerability and consequences, and resulting in a numerical value of the risk.

Recurrence Interval (repeat period) – An estimated value of how often an event occurs based on the average time between passed events.

Regression – The continual movement of a landslide downslope and or widening/retreat of the headscarp.

The **Regulator** will be the responsible body/authority for setting Acceptable/Tolerable Risk Criteria to be adopted for the community/region/activity, which will be the basis for setting levels for Acceptable and Tolerable Risk in the application of the risk assessment guidelines.

Risk – A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by the product of probability x consequences. However, a more general interpretation of risk involves a comparison of the probability and consequences in a non-product form.

Risk Analysis – The use of available information to estimate the risk to individuals, population, property or the environment from hazards. Risk analyses generally contain the following steps: scope definition, hazard identification and risk estimation.

Risk Assessment – The process of risk analysis and risk evaluation.

Risk Control or Risk Treatment – The process of decision making for managing risk and the implementation or enforcement of risk mitigation measures and the re-evaluation of its effectiveness from time to time, using the results of risk assessment as one input.

Risk Estimation – The process used to produce a measure of the level of health, property or environmental risks being analysed. Risk estimation contains the following steps: frequency analysis, consequence analysis and their integration.

Risk Evaluation – The stage at which values and judgements enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences, in order to identify a range of alternatives for managing the risks.

Risk Management – The complete process of risk assessment and risk control (*or risk treatment*).

Runout Distance – The horizontal distance from the source area to the distal toe.

Susceptibility – see Landslide Susceptibility

Temporal-Spatial Probability – The probability that the element at risk is in the affected area at the time of the landslide.

Tolerable Risk – A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if possible.

Transgression-regression cycles – Sedimentary deposits formed from cycles of sea level rise and fall.

Travel Angle – The angle from the crest of the source area to the distal toe of the debris (run out zone)

Vulnerability – The degree of loss to a given element or set of elements within the area affected by the landslide hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss). For property, the loss will be the value of the damage relative to the value of the property; for persons, it will be the probability that a particular life (the element at risk) will be lost, given the person(s) is affected by the landslide.