Auckland Region Landslide Susceptibility Assessment

Technical Report TR2025/7

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Auckland Council

Engineering Assets and Technical Advisory Department

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This report provides a less technical introduction to the more detailed *Auckland landslide susceptibility study* technical report, WSP March 2025. **[Included in this report, pages 36-202]**

Auckland Council technical report, TR2025/7

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Part 1: Cover Report

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Executive summary

Landslides are one of New Zealand's – and Auckland's - most significant natural hazards. Auckland Council has a range of strategies to proactively manage the risk from natural hazards and enhance the resilience of the region to these hazards, including landslides. As experienced in the 2023 storm events, landslides present a life safety risk, adversely affect property and infrastructure, and may damage or destroy cultural and environmental sites.

This summary report introduces a more detailed study that was undertaken across the full Auckland region to understand areas susceptible to landslides. This work was undertaken to improve our (and Aucklanders) understanding and mapping of landslide hazards across the region, and to inform more effective land use planning and planning decisions.

Landslide susceptibility models analyse different terrain features to show where landslides are more or less likely to occur. This gives us an understanding of 'what could go wrong where' (susceptibility) but not 'how often might this occur' (hazard).

The purpose and outcomes of this analysis and mapping is to:

- Provide information and collective understanding on the distribution of landslide-susceptible areas across the region, so that this can be taken into consideration in proactive land use, growth and infrastructure planning.
- Help facilitate the development of district planning regulations to allow proactive management of the risks associated with development.
- Aid and enhance regional emergency response planning.

In most cases, the best way to manage the risk from landslides is to avoid building in areas of higher risk. While the risk can be engineered out in some cases, doing this is costly and not always effective. This study does not provide information at a level of detail appropriate for supporting the design of engineering solutions for land instability. However, it can be used to identify areas where caution should be applied and where further assessment would be appropriate.

1.0 Introduction

1.1 Background

Landslides are one of New Zealand's most significant natural hazards. Since 1760 there have been at least 1,500 deaths from landslides in New Zealand. Over the last 160 years, more fatalities occurred from landslides than from earthquakes (501), volcanic activity (179) and tsunami (one).

Tāmaki Makaurau's diverse landscape with many hilly areas and underlying geology is prone to landslides from rainfall triggers. To increase Auckland's resilience to landslides we need to understand where they occur, and what we can do to reduce the risk in areas with greater susceptibility to landslides.

The most effective way to manage the risk of landslides is often to avoid building in higher risk areas. While the risk can be engineered out in some cases, doing this is costly and not always effective. As the region grows there will be further demand for suitable places to build, with increased risk of building on marginal or unsuitable land.

Our existing land-use planning controls for landslide risk are incorporated into Chapter E36 of the Auckland Unitary Plan. This chapter provides written descriptions of characteristics which can make a site susceptible to landslides and were developed based on expert judgement when the plan was developed. This approach has several limitations. Because of the written format, it is not possible to map the locations, making it challenging to enforce and hard for applicants to know when the provisions will be triggered. Even though it is based on expert judgement, it is hard to validate the accuracy and to improve the controls over time.

To mitigate these issues, Auckland Council developed a landslide susceptibility map for the region. For this approach to be scientifically robust and defensible, it requires a comprehensive inventory of past landslides but unfortunately, up until recently, this has not been available. As a first stage of this project, Auckland Council developed a landslides database and began to populate it in 2022.

In 2023, Auckland experienced over 50,000 landslides triggered by severe weather (Auckland Anniversary storm and Cyclone Gabrielle). This impacted lives, homes, roading networks and had many other built, social, environmental and economic impacts (Figure 1 and 2). However, it did provide a large dataset of landslides on which an inventory could be developed and allowed the development of the landslide susceptibility mapping to be accelerated. A study was initiated out of the recovery efforts in 2023 forming the basis of the *Auckland Landslide Susceptibility Study* Technical Report 2025[1] for the region.

This report provides a less technical introduction to the more detailed *Auckland Landslide Susceptibility Study* Technical Report 2025.

[1] WSP Landslide Susceptibility Study Technical Report. WSP. March 2025.

Figure 1: Landslides at Muriwai, triggered from the Cyclone Gabrielle. Source: GNS

Figure 2: Landslide on Manukau Heads Road, Awhitu Peninsula. Source: GNS

1.2 Purpose, scope and limitations

The objective of this study is to map areas susceptible to landslides across the Auckland region (Figure 3) to inform land-use planning. The landslide susceptibility maps produced from this study show where landslides are more and less likely, which is a useful first pass for risk-reduction and land-use planning. This is a regional-level assessment and not intended for site-specific use without further, more detailed assessment.

The purpose of this study is to:

- Provide information on the distribution of landslide-susceptible areas across the region, so that this can be taken into consideration in proactive land use, growth and infrastructure planning.
- Help facilitate the development of district planning regulations to allow proactive management of the risks associated with development.
- Aid and enhance regional emergency response planning.

The scope of the study was to:

- Collate a landslide inventory for the region from existing information and further desk-based mapping.
- Complete a region-wide assessment of landslide susceptibility and produce maps indicating areas that have the potential for landslides.

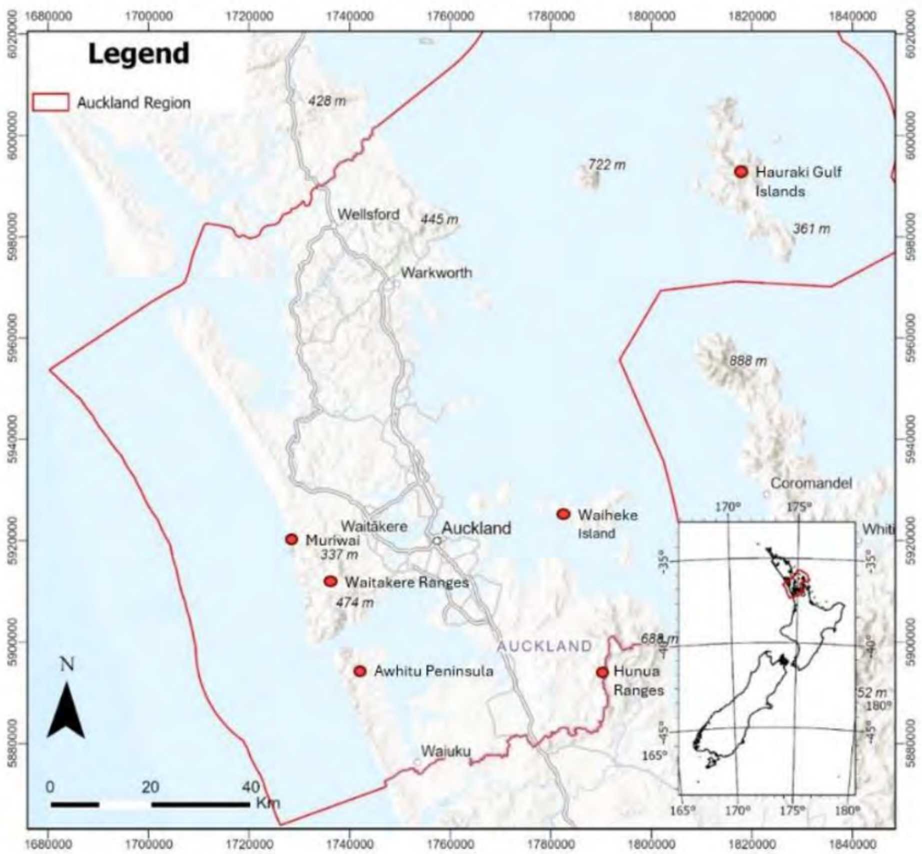

Figure 3: Area Extents of the Study, Auckland region

This study presents two landslide susceptibility maps:

1) Susceptibility to generally smaller scale and shallow landslides, which tend to form in near-surface materials and can have damaging impacts across small areas.
2) Susceptibility to larger scale landslides, which are often much deeper, sometimes slower moving, and cause damage across a wider area, often over a longer period.

These two classes of landslide are mapped separately as the underlying drivers can be different, and the planning and engineering controls that are most effective are also different. The method used to develop these maps is explained in the following sections.

The work was scoped and directed by Auckland Council geotechnical and geological staff and delivered by WSP. A technical review group with expert representatives from academic and professional backgrounds was engaged to provide an independent review.

Key limitations of this study include:

- The maps do not show areas of uphill regression of existing landslides, or downhill runout of landslide debris, because there was insufficient information available to appropriately predict where future regression would occur or where debris flows would travel.
- The accuracy of the mapped susceptibility is a function of the completeness of the landslide inventory. Because the inventory is dominated by landslides resulting from the 2023 storms, there may be some bias in the assessment towards similar events.
- The maps do not address earthquake-triggering of landslides (although slopes which are susceptible to rainfall induced landslides are likely to be similarly susceptible to earthquake induced landslides).
- Shallow landslides are mapped on a 32m x 32m grid, and large-scale landslides on a sub-catchment scale. Some of the input factors (such as geological maps) are lower detail. This means that the results should not be relied upon at a local level without more detailed assessment.
- Not all landslide types are included in the landslide inventory, meaning that the susceptibility mapping does not represent them. This includes rockfall and toppling. This is because these events tend to be less significant in the Auckland region.
- Susceptibility mapping based on landslide inventories does not take into account climate change effects.

It is expected that further work will be undertaken in the future to allow improvements to this mapping to help mitigate some of these limitations.

1.3 Introduction to landslides

Landslides are the downslope movement of earth materials such as rock, soil and debris. Other terminology is sometimes used for landslide type features such as ‘landslip’, ‘slippage’ and ‘falling debris’ (these older terms are used in the Resource Management Act 1991 or the Building Act 2004).

1.3.1 What causes landslides

To understand what causes a landslide it's important to differentiate between underlying drivers and triggers. The underlying driver of slope instability is the balance between load applied to a slope and the strength of the material. When the effect of loading overcomes the strength of the soil or rock, the slope will fail. The primary cause of loading on slopes is gravity, and the load this imposes is directly related to the topography of the slope. The material strength is a function of the site geology.

Triggers, which tip a marginally stable slope into failure, are more varied. They can be split into factors that reduce the strength, those that increase the load, and those that change the geometry of the slope (Table 1).

Table 1: Common triggers of landslides split by factors.

Strength reducing factors	• Groundwater pressure increases (soil or rock strength is directly reduced by pore water pressure). This can be caused by many factors including high rainfall, leaking pipes, changing climate, and geothermal activity. • Weathering of the surface materials, often over a prolonged time period. • Loss of vegetation which may have previously reinforced the slope. This can occur naturally (e.g. as the result of fires) or by human activity. This can also have the effect of increasing groundwater pressures as the plants would have abstracted water from the slope.
Load increasing factors	• Earthquakes. • Rainfall, saturating the ground and increasing the load. • Placement of fill on the slope or on top of the slope. • Buildings, equipment or materials stored at the top of a slope. • Vibrations from machinery, blasting or construction.
Geometry changing factors	• Erosion of the toe (bottom) of the slope, often by a river or the sea. • Excavation of the toe as part of construction or quarrying. • Placement of unstable fill. • Volcanic or tectonic activity steepening slopes.

1.3.2 Landslide types

The movement of material downslope can be classified into different types (Figure 4). The types of landslides that occur are highly dependent on the underlying geology and geomorphology (e.g. a coastal cliff top versus an inland high-country paddock) and other external processes.

These classifications are useful because different landslides types have different potential triggers, consequences, and feasible controls.

An alternative grouping of landslides classes into broader 'susceptibility classes' that can be understood and managed in similar ways allows for logical controls to be put in place. The grouping is determined based on local conditions, to reflect the types of landslides that occur in any specific region.

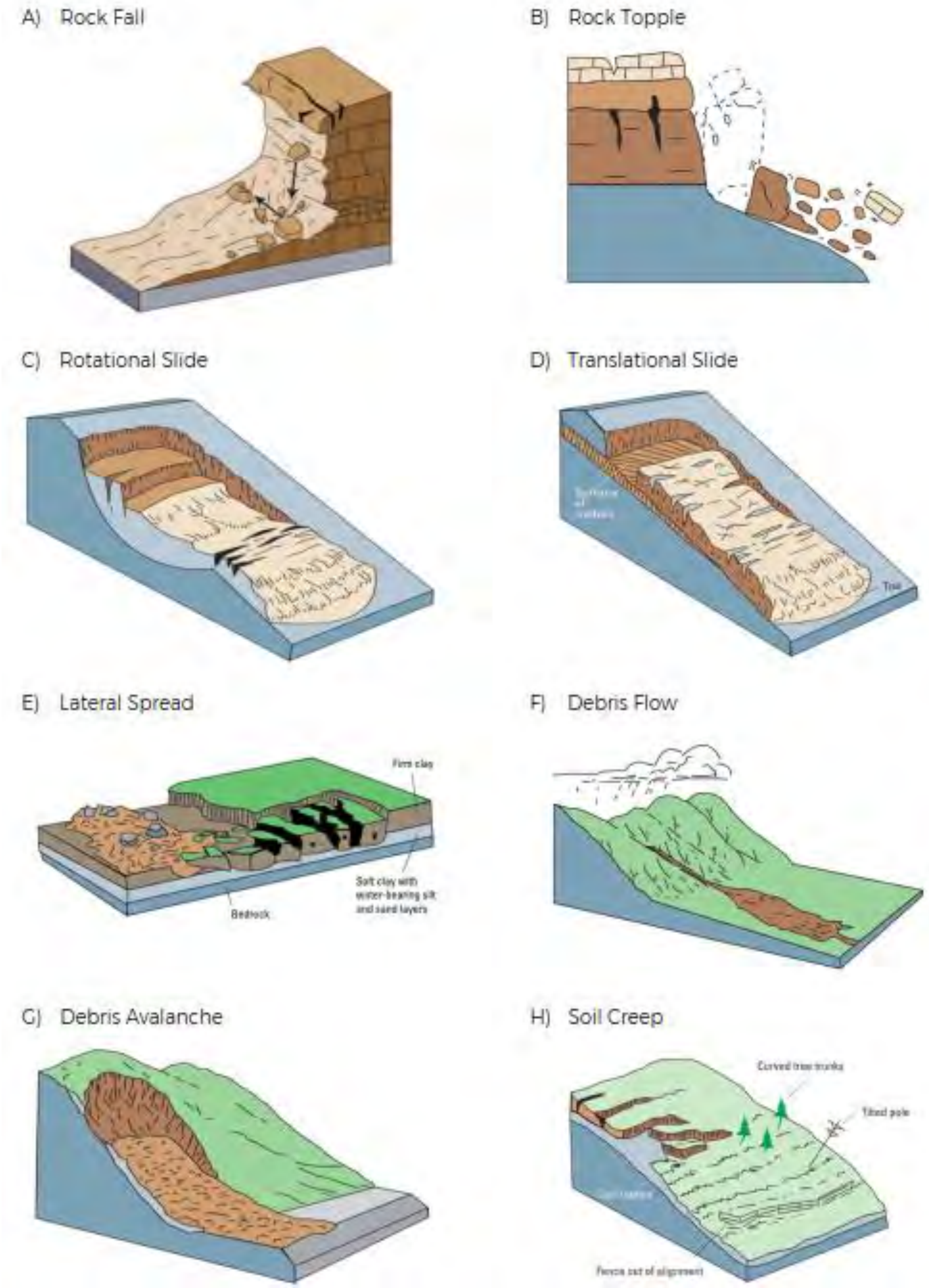

Figure 4: Schematic block diagrams of different landslide types, (from Highland & Bobrowsky, 2008)

1.3.2.1 Components of landslides

It is important to understand that there are different hazard zones within landslides (Figure 5); these include:

- Regression Zone
- Failure Zone
- Deposition Zone
- Runout Zone

For this study the failure and deposition zones were the focus of the analysis to identify susceptible areas and did not include the full runout zone.

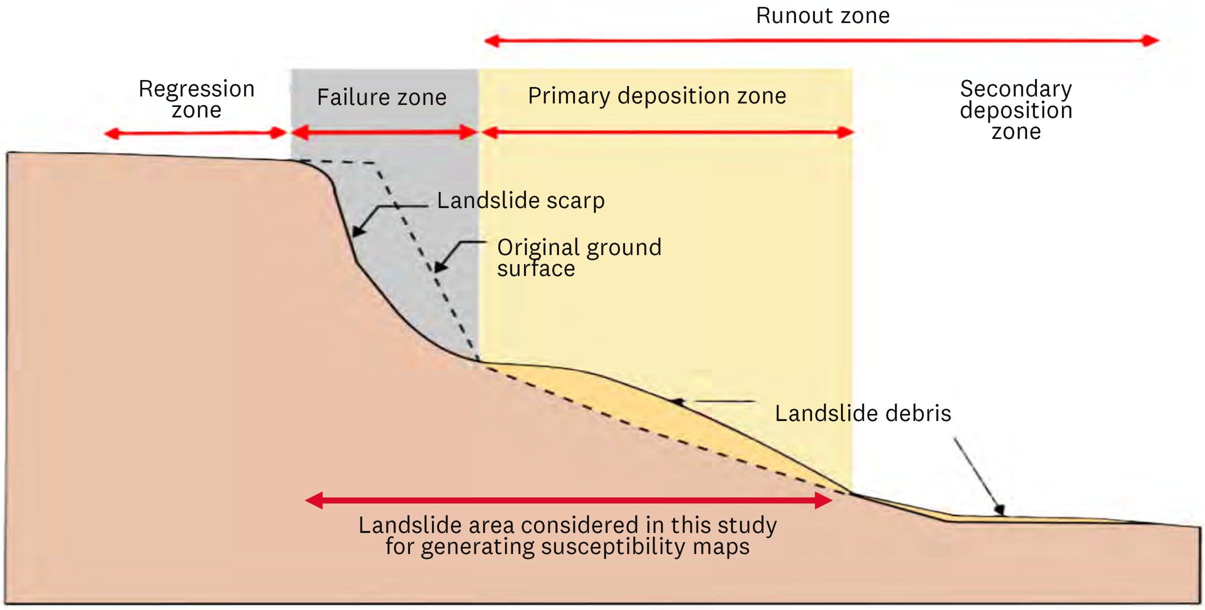

Figure 5: Diagram of different landslide hazard zones and the extent of the landslide area considered in this study for generating susceptibility maps (WSP Landslide Susceptibility Study Technical Report)

1.3.2.2 Shallow and large scale landslides

In assessing the susceptibility of the region to landslides, we have differentiated two 'susceptibility classes' of landsliding for the Auckland region:

- Shallow landslides and debris flows = **'shallow landslides'**
- Large scale, slow-moving or relict landslides = **'large scale landslides'.**

'Shallow landslides' tend to be small failures within the shallow near-surface soil and rock materials where the proportion of the affected area of slope is small (these features are typically tens to hundreds of square metres in area). These failures are often triggered by prolonged or intense rainfall events and are generally rapid (>1.8 m/hour) to extremely rapid (>5 m/second).

'Large scale landslides' generally span over most of the hillslope (these features are typically thousands to hundreds of thousands of square metres in area). These are normally related to deeper geological structures and groundwater conditions, and other longer-term landscape-scale processes such as tectonic uplift and fluvial incision (particularly toe erosion causing de-buttressing of susceptible hillslopes) and tend to be slower moving.

1.4 Introduction to landslide susceptibility

Landslide susceptibility describes the relative likelihood of future landsliding in an area based on underlying properties (i.e. is one area more or less susceptible than another area to landsliding). It does not include how often landslides might occur, or the consequences.

Landslide susceptibility maps are different from landslide hazard maps. Susceptibility maps show where landslides might occur, whereas hazard maps also take into account how often a landslide might occur, and how large and fast it might be. They show a higher level of hazard in areas where damaging landslides are likely to occur more often. Landslide susceptibility mapping does not quantify the number of landslides which may occur in each time period, nor the annual probability of these events occurring as this type of output is considered hazard mapping.

Landslide susceptibility models analyse different terrain features to show where landslides are more or less likely to occur. This therefore gives us an understanding of '***what could go wrong where'*** (susceptibility) but not '***how often might this occur and where'*** (hazard).

Susceptibility mapping has the benefit of simplicity. Hazard mapping requires several decades (ideally centuries) of landslides to be recorded in an inventory to be reliable. Susceptibility mapping does not need this level of detail.

Table 2: Description of terms Landslide susceptibility, hazard and risk.

Term	Definition	Notes
Landslide susceptibility	Where landslides are more or less likely to occur	• This does not indicate how likely a landslide is, simply that it is more or less likely than other areas. • A site which could have a landslide every ten years would be treated the same as a site that could have a landslide every 50 years.
Landslide hazard	Where landslides are likely to occur more frequently	• This gives an indication of how likely a landslide is, but not of whether the consequences are important. • A landslide in a forest would be treated the same as a landslide in a suburban area.
Landslide risk	The consequences of the landslide hazard and its likelihood	• This considers how much damage the landslide would cause to things we value like homes, infrastructure or the environment, and how likely is such damage. • The risk would change if the use of the site changed, which makes it challenging to keep this type of mapping current, or to make it relevant for future (potentially unforeseeable) land uses.

By comparison, flooding hazards have a much longer record of past events, and more comprehensive modelling options are available. As a result Auckland's flood maps are able to show flood hazard, rather than susceptibility.

GNS Planning Guidelines divide landslide susceptibility, hazard and risk analysis into five categories:

- Level A: Landslide Susceptibility Analysis (this regional study)
- Level B: Landslide Hazard Analysis
- Level C-E: Landslide Risk Analysis

GNS planning guidance recommends a minimum of a 'Level A' simple assessment for every region across New Zealand to inform strategies and plans. Auckland Council selected Susceptibility Analysis as the most appropriate type of mapping because we do not yet have sufficient historical landslide records to generate a reliable hazard analysis consistently for the whole region.

It is important to note this study at a Level A would not supersede any greater level of assessment that has already been undertaken, e.g. a property-level landslide risk assessment that was undertaken as a result of a landslide during the 2023 severe weather events (or similar) risk assessments.

Table 3: GNS Planning Guidance for Landslides level of analysis overview.

LEVEL A **Susceptibility analysis**	• A susceptibility analysis involves mapping existing landslides and land potentially susceptible to landslides (This study)
LEVEL B **Hazard analysis**	• Uses the outcomes of the landslide susceptibility mapping and assigns an estimated frequency to the potential landslides
LEVEL C **Semi-quantitative analysis**	• Different levels of risk analysis considering elements at risk, exposure and vulnerability (for example Waitakere Coastal Communities Landslide Risk Assessment Overall Report – Muriwai)
LEVEL D **Basic quantitative risk analysis**	
LEVEL E **Detailed quantitative risk analysis**	

1.5 Climate change and landslides

Climate change will exacerbate landslide hazards over time (de Vilder et al. 2024). However, because landslide susceptibility maps are generated from inventories of existing landslides, they are inherently 'backwards looking' – they assess the susceptibility based on the past, not the future.

It is likely that climate change will make landslides more frequent, and for them to occur in areas where previously they would have been unlikely. Because landslide susceptibility is independent of how often landslides occur, the first factor (increased frequency) does not reduce the accuracy of susceptibility maps. The potential for landslides to occur where they haven't been common in the past is a potential weakness of the susceptibility analysis approach. This weakness can be compensated for by taking a conservative approach to managing risk in areas of moderate susceptibility.

1.6 Legislation, standards and guidelines

There is no single statute that provides the framework for managing natural hazards (including landslides), but there are five pieces of legislation that are directly relevant to the management of natural hazards in New Zealand.

1.6.1 Resource Management Act 1991 (RMA)

The RMA is New Zealand's primary environmental legislation. It defines natural hazards broadly, including events like earthquakes, tsunamis, erosion, and flooding. The Act requires local authorities to manage land use to avoid or mitigate natural hazards. This is done through regional and district plans, which can designate "Hazard Areas" with specific rules. The RMA emphasises the importance of managing significant risks from natural hazards as a matter of national importance.

1.6.2 Building Act 2004

This Act focuses on building safety and has a narrower definition of natural hazards than the RMA. It includes hazards such as erosion, falling debris, subsidence, inundation, and slippage. A consent may only be issued if the territorial authority is satisfied that adequate provision will be made to protect, or restore any damage, to the land, the building work or other property, or if a Section 72 waiver is appropriate.

1.6.3 Civil Defence Emergency Management Act 2002 (CDEM Act)

The CDEM Act takes a comprehensive approach to hazard management and emergency response. It requires regional councils and territorial authorities to form Civil Defence Emergency Management Groups. These groups must assess and manage hazards and risks in their areas and prepare plans that identify hazards and outline cost-effective risk reduction measures. The Act emphasises public consultation in the planning process and promotes a "4 R’s" approach: reduction, readiness, response, and recovery.

1.6.4 Local Government Act 2002

This Act focuses on the long-term planning and infrastructure management responsibilities of local authorities. It requires councils to develop infrastructure strategies that address resilience to natural hazards. These strategies must identify risks from natural hazards and make financial provisions for increasing resilience. This approach ensures that natural hazard management is integrated into the broader planning and budgeting processes of local governments.

1.6.5 Local Government Official Information and Meetings Act 1987

Under this Act, local government has an obligation to identify natural hazards relating to a property, which are known to us, and include this information on Land Information Memorandums (LIM). A LIM must include "information identifying each (if any) special feature or characteristic of the land concerned, including but not limited to potential erosion, avulsion, falling debris, subsidence, slippage, alluvion, or inundation [...] being a feature that is known to the territorial authority but is not apparent from the district scheme...or district plan".

2.0 Data and methods

The study methodology included:

- Collating data including geology, topography, waterways, land use etc.
- Collating an inventory of past landslides from existing sources as well as new desk-based mapping
- Statistically assessing the susceptibility of the land to landslides considering a variety of factors that contribute to the potential slopes to fail
- Classifying the land into five landslide susceptibility classes

These methodologies followed the same principles of analysing potential landslide-inducing variables and assessing landslide susceptibility based on local conditions and existing mapped landslides. Statistical analysis of the landslide inventory, local site conditions and professional judgement were used to inform the relative importance of specific variables to landslide susceptibility.

2.1 Geomorphological sub regions

The types of landslides that occur are strongly linked to geomorphic processes and underlying geology. For the purpose of assessing and classifying landslide susceptibility, the region was separated into sub-regions (Figure 6) based on its geology and geomorphology.

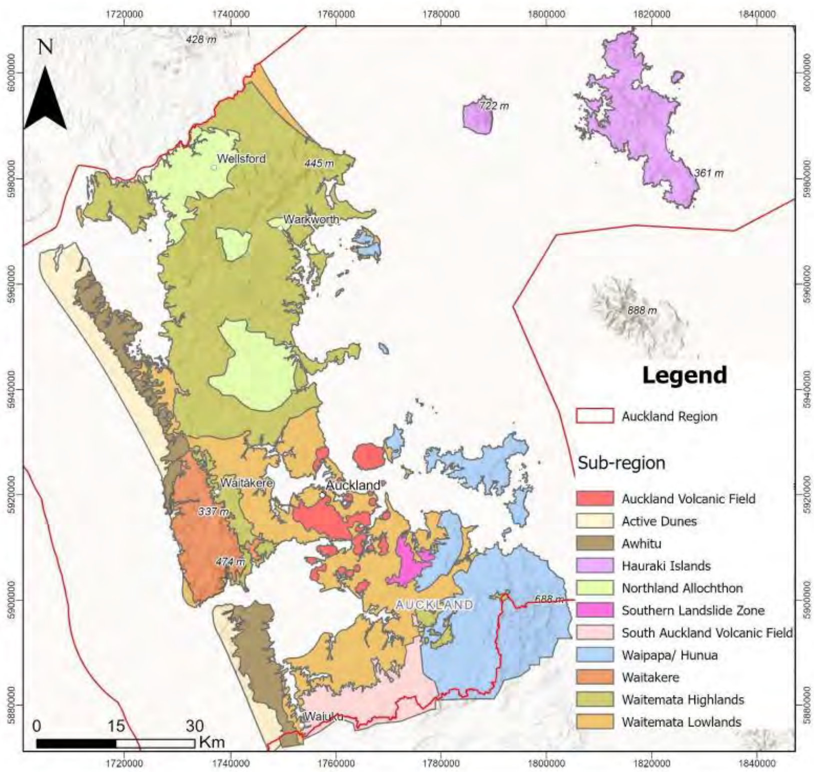

Figure 6: Map of the Auckland region classified into 11 geomorphic sub-regions. Adapted from Edbrooke et al (2002).

2.2 Landslide inventory

To predict where landslides may happen in future, it's important to have a reliable dataset of past events to extrapolate from (e.g. with a large dataset we can identify if one specific geology type is more susceptible to landslides and manage the hazard accordingly). Having a landslide inventory available can also help with decisions made on specific sites where landslides previously occurred.

Because there's no single entity in New Zealand with responsibility for doing this, there is no single source of truth. Recognising this as a gap in our understanding, Auckland Council partnered with the Natural Hazards Commission Toka Tū Ake (formally EQC) to develop the NZ Landslides Database and started to populate it with landslide data. The database went live in the second half of 2022, meaning it was available for immediate use in the storm events of 2023 (Auckland Anniversary Floods and Cyclone Gabrielle). Since then, 150,000 records have been added.

A regional landslide inventory was compiled from existing landslide maps on the NZ Landslides Database, other external sources and additional mapping for this project. Many of the landslides that occurred in 2023 were mapped and compiled with other landslide data to create a reliable landslide inventory.

These additional landslides (Figure 7) were added to the NZ Landslides Database for others to benefit from.

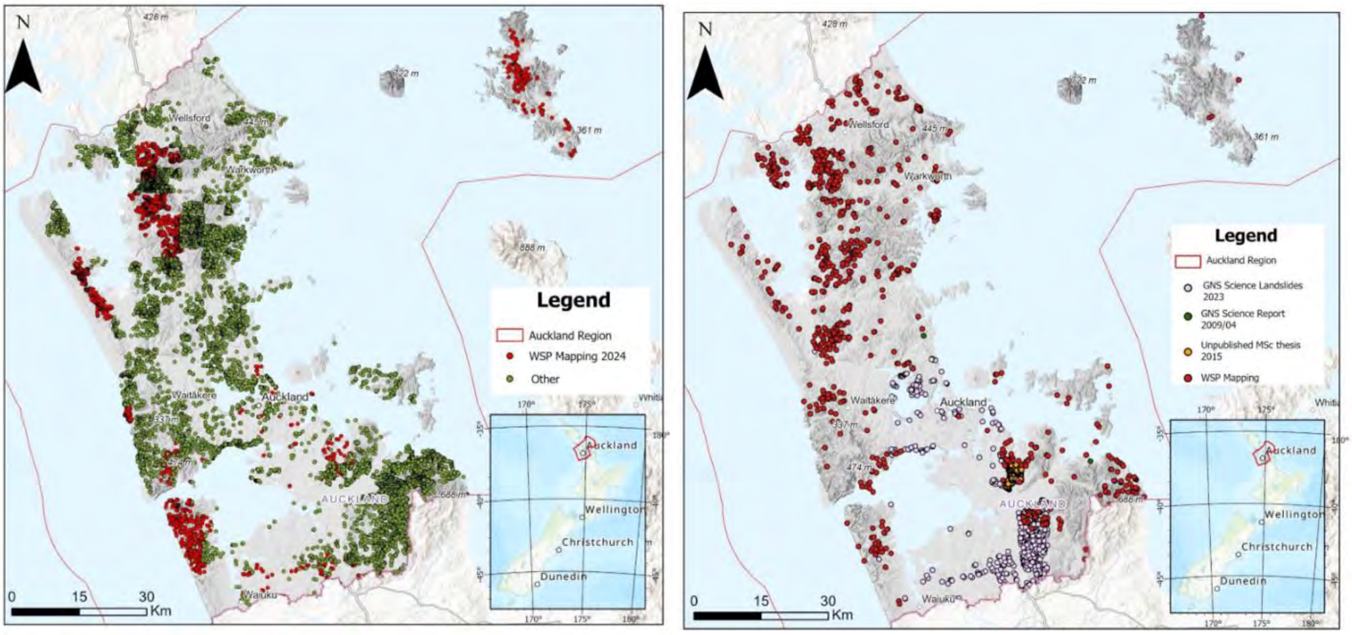

Figure 7: a) map of the shallow landslide inventory b) map of large scale landslide inventory

2.3 Scale of assessment and scale of the maps

Landslide susceptibility mapping represents a desk-based, region-wide assessment. No access was gained to properties, and site-specific assessments have not been undertaken. Therefore, when viewing the maps, a suburb-level view is recommended for the shallow landslide susceptibility map and town-scale for the large scale landslide susceptibility map:

- Shallow landslide susceptibility map - 1:25,000 scale = roughly suburb level
- Large scale landslide susceptibility map - 1:50,000 scale = roughly town level.

3.0 Results

Landslide susceptible areas in Auckland have been assessed and mapped according to international and local guidelines, achieving a ‘Level A’ analysis as per Planning Guidelines (de Vilder et al, 2024).

Five classes of landslide susceptibility are described, from Very Low to Very High, and these are mapped across the region showing the spatial distribution and extent of the different susceptibility classes. These maps, shown below (Figure 9, Figure 11), highlight areas more susceptible to landslides such as the Hunua and Waitākere Ranges, coastal bluffs and generally steep gullies.

The maps exclude site-specific conditions and features below the resolution threshold, meaning detailed assessments remain necessary for accurate site-specific risk determination. Despite this, the landslide susceptibility maps offer important information to guide land use planning, urban growth strategies, helping to steer development away from potentially high-risk areas and toward lower risk.

3.1 Shallow landslide susceptibility

Figure 8 shows how landslides in the inventory correlate with the assigned susceptibility categories. If the correlation was poor, the landslides would be spread across each of the different susceptibility classes. A strong correlation puts most of the landslides into the higher categories of susceptibility. Because of site-specific details that a regional study cannot identify, there will always be some landslides that occur even in the lowest classes, but they should be small in number.

This analysis shows that the model is robust, highlighted by the fact that 47% of the land area is designated very low susceptibility, and only 2% of mapped landslides occur in this area (Table 4).

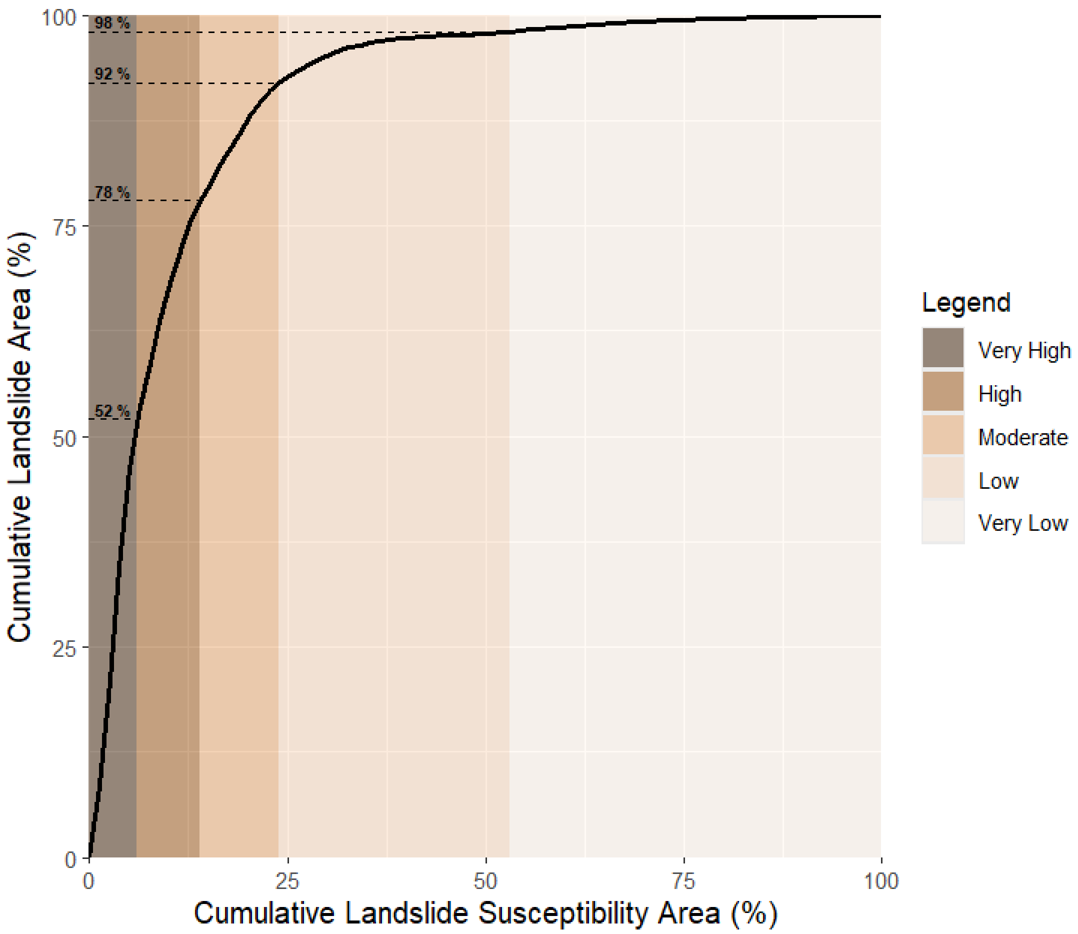

Figure 8: Cumulative shallow landslide susceptibility area by percentage

Table 4: Shallow landslide susceptibility classification summary

Susceptibility class	Study area		Slope unit landslide inventory			
	Area in class (km²)	Proportion of total area of region	Area of landslides in class (km²)	Proportion of total area of landslides	Proportion of total area of class	Proportion of total area of region
Very Low	2,308	47%	6	2%	0.3%	0.1%
Low	1,451	29%	24	6%	1.7%	0.5%
Moderate	478	10%	53	14%	11.2%	1.1%
High	400	8%	97	26%	24.1%	2.0%
Very High	288	6%	195	52%	67.6%	4.0%

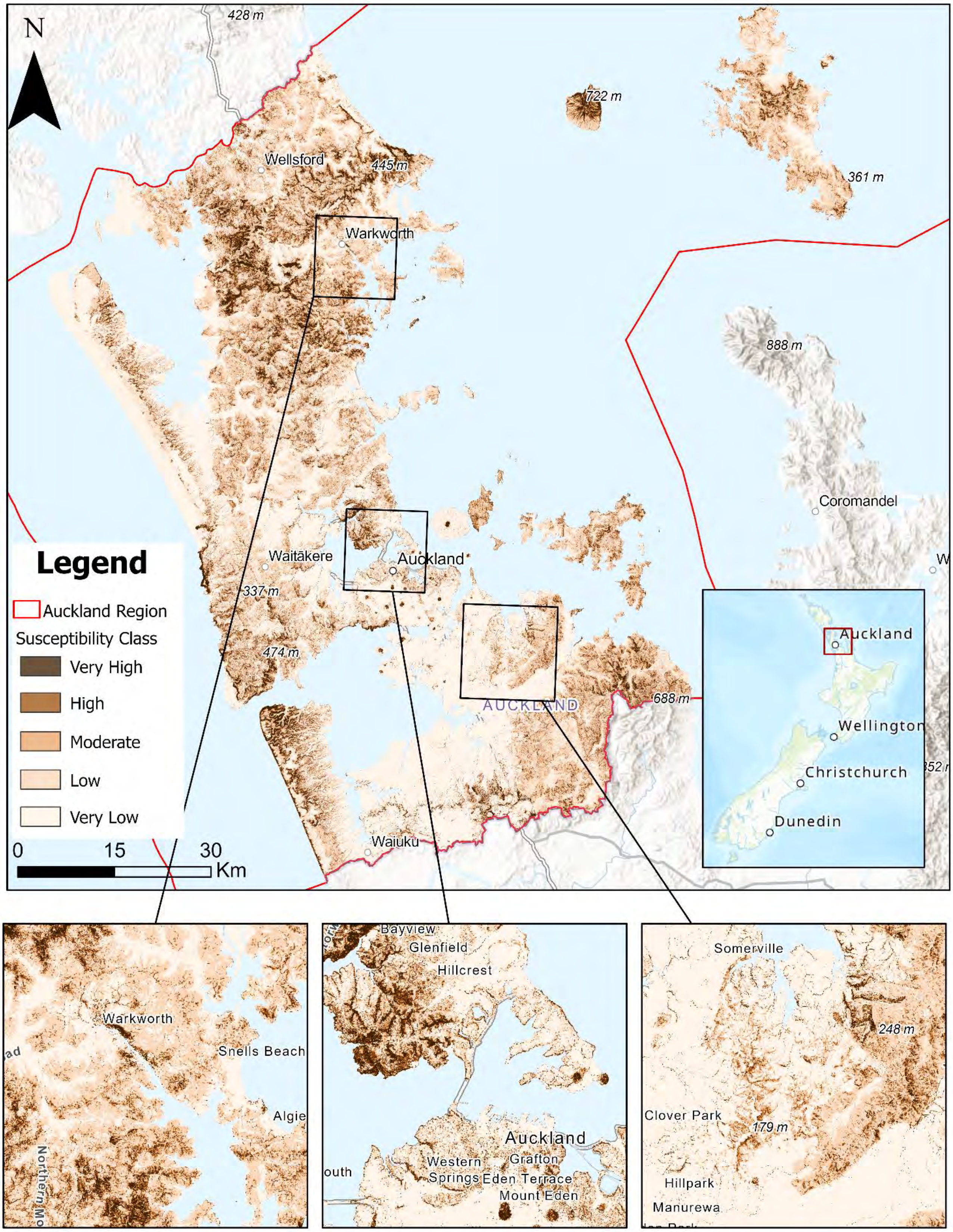

Figure 9: Shallow landslide susceptibility map

3.2 Large scale landslide susceptibility

Figure 10 shows how landslides in the inventory correlate with the assigned susceptibility categories. This analysis shows that the model is robust, highlighted by the fact that 25% of the land area is designated very low susceptibility, and only 1% of mapped landslides occur in this area (Table 5).

Previous investigations have highlighted geomorphological areas such as Northland Allochthon (Figure 6) and the Southern Landslide Zone to be susceptible to large scale landslides. This is reflected in the results, with the Northland Allochthon, Southern Landslide Zone, and Waitemata Highlands sub-regions assessed as having the highest susceptibility to large-scale landslides while the Hauraki Islands, Waitakere Ranges and the Auckland Volcanic Field are assessed to be less susceptible (Figure 11).

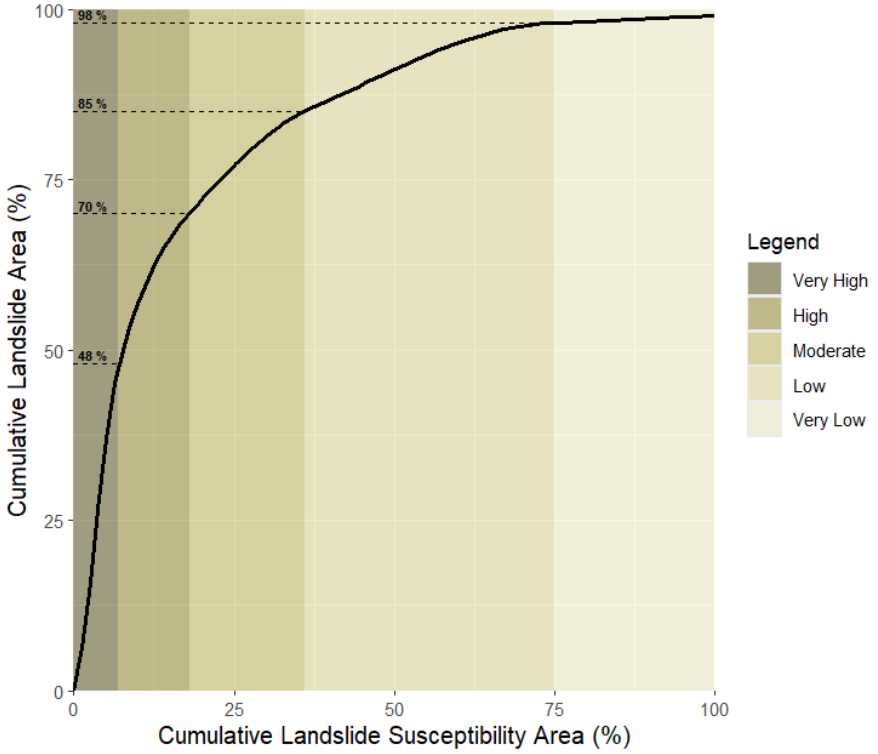

Figure 10: Cumulative large scale landslide susceptibility area by percentage

Table 5: Comparison of landslide susceptibility classes to large scale landslide inventory

Susceptibility class	Study area		Slope unit landslide inventory			
	Area in class (km²)	Proportion of total area of region	Area of landslides in class (km²)	Proportion of total area of landslides	Proportion of total area of class	Proportion of total area of region
Very Low	1,201	25%	4	1%	0.3%	0.1%
Low	1,927	39%	37	13%	2%	0.8%
Moderate	893	18%	44	15%	5%	0.9%
High	525	11%	64	22%	12%	1.3%
Very High	344	7%	139	48%	40%	2.8%

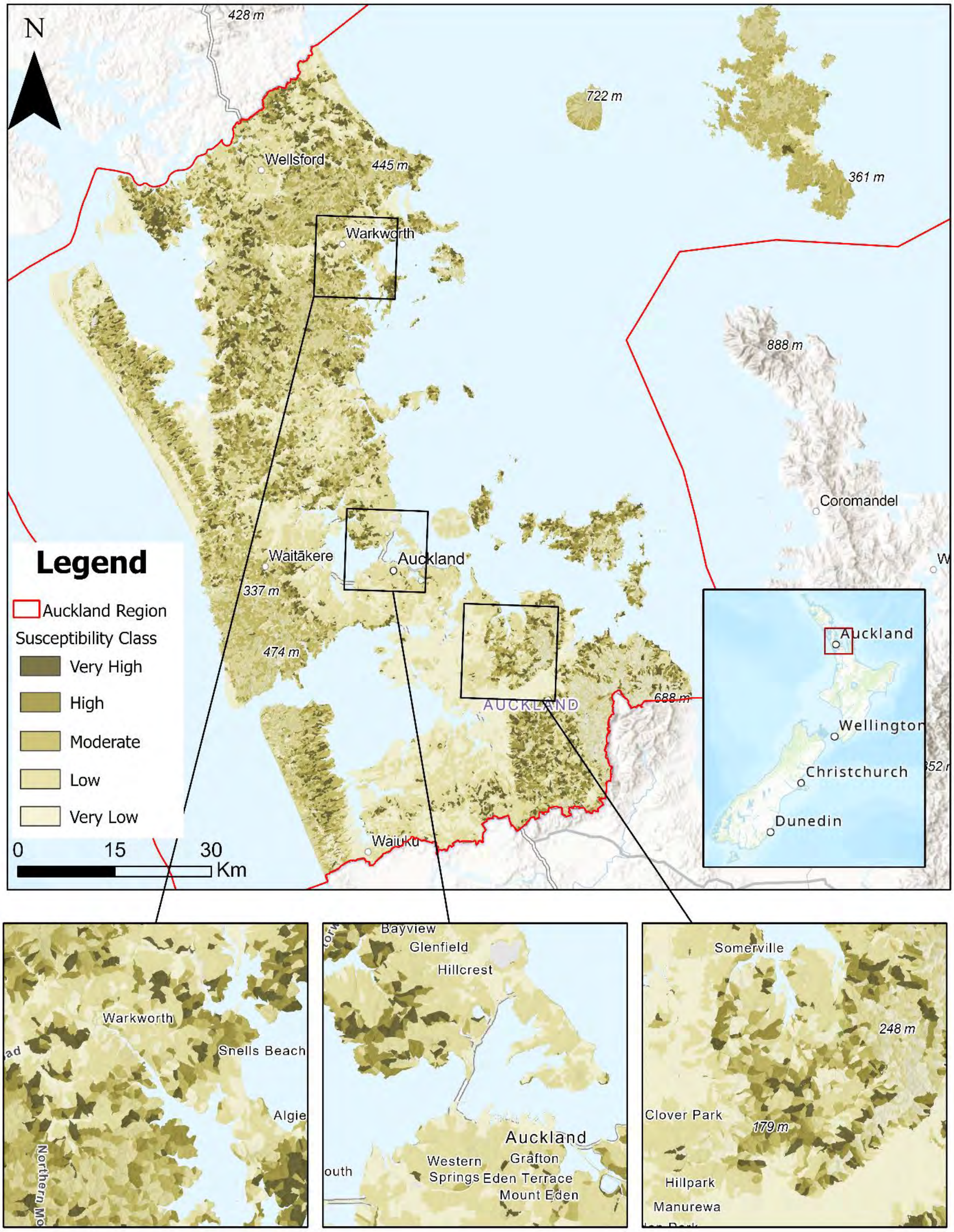

Figure 11: Large scale landslide susceptibility map

3.2.1 Total area affected per susceptibility class

The land has been divided up for both landslide styles (shallow and large scale) on the maps. The maps identify the susceptibility of slopes to landslides on a scale of:

- Very low
- Low
- Moderate
- High
- Very high

The total area affected in each of these classes can therefore be summarised by showing its combined percentage area affected within each class (Appendix A). The chart below (Figure 12) shows approximately how much of Auckland's area is affected by each susceptibility class, either in shallow or large scale landslides as approximate percentages of land area.

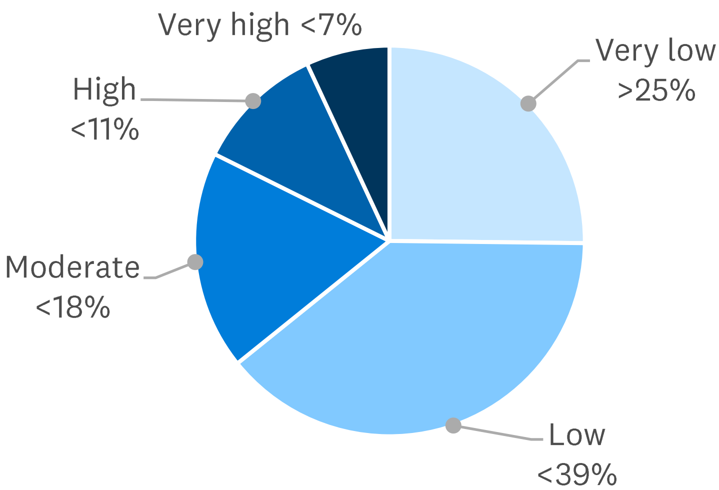

Figure 12: Pie chart showing approximate percentage of land area for the Auckland Region in either shallow or large scale landslide susceptibility per susceptibility classification (Very Low – Very High)

Showing combined totals where either shallow or large scale landslide susceptibility applies means that it presents the 'worst case' values for the higher susceptibility classes to allow consideration of the total area that might be affected, for example by changes in planning rules. It should be noted that higher susceptibility classes tend to correspond with less developed land.

It has not yet been decided which classes will have land use planning controls assigned to them, or what those controls will be. Further consultation will take place through the plan change process.

3.3 How to view results

These maps will be placed on Auckland Council GIS platform, and in time will be available to view through a few sources.

- **GeoMaps is our Geographic Information System (GIS) viewer. It contains spatial and non-spatial information from across Auckland.**

4.0 Next steps

These maps will be used to inform future changes to the Auckland Unitary Plan, noted on LIMs to inform future owners of the potential hazard and used in decision-making for Auckland Council when identifying areas for development or for building our assets.

We will continue to support the NZ Landslides Database to improve our understanding of the landslide hazards and are working with researchers to continually enhance our modelling of the landslide hazards and risks so that future iterations of this mapping will be even more reliable.

We will continue to support research into landslide hazard which will help reduce the risk for Aucklanders. Current related projects include:

- GNS mapping of landslides in the Auckland region, Pukekohe and Silverdale (Auckland Council commissioned).
- Sliding Lands, Hōretireti Whenua: The programme is led by GNS Science, with research partners Massey University, Manaaki Whenua Landcare Research, Te Runanganui o Ngāti Porou, Market Economics, University of Auckland, Resilient Organisations and University of Canterbury (https://www.gns.cri.nz/research-projects/sliding-lands/). This programme will create national-scale landslide models that can forecast where rapid and dangerous landslides are likely to be triggered by earthquakes and rainfall events.
- Landslide Watch Aotearoa: Also led by GNS Science, this programme aims to move away from expensive local reactive (post-event) in-situ monitoring to pro-active (pre-event) space-based observation across all Aotearoa. The team propose to use satellite data (InSAR) to detect slow-moving landslides, link their movement patterns to the climatic drivers and characterise their behaviour before they cause damaging and/or catastrophic impacts.

Further reading

Mason, D., Brabhaharan, P., Eastaugh, E., Rozmus, K., Porter, H., Goldsworthy, M., Patel, J., Barnhill, D., George, A. (2025). Landslide Susceptibility Study. WSP Report No. GS 2025 – 09. February 2025 (INCLUDED HEREIN, 34-201).

de Vilder, S. J., Buxton, S. D., Allan, S., & Glassey, P. J. (2024). Landslide planning guidance: reducing landslide risk through land-use planning. GNS Science. GNS Science miscellaneous series 144. 84 p https://www.gns.cri.nz/assets/MS-144-Landslide-Planning-Guidance_2024-UPDATE.pdf

AGS. (2007a). Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning. Journal and News of the Australian Geomechanics Society, 42(1), 13-36. https://landsliderisk.org/resources/guidelines/

Appendix

Appendix A

OR %		Shallow				
		Very Low or higher	Low or higher	Moderate or higher	High or higher	Very High
Large	Very Low or higher	100	55.55	24.71	14.53	6.19
	Low or higher	74.82	49.54	22.03	12.92	5.51
	Moderate or higher	35.79	26.46	11.15	6.17	2.37
	High or higher	17.66	13.25	5.47	2.98	1.14
	Very High	6.93	5.19	2.17	1.22	0.51

Appendix B

AND %		Shallow				
		Very Low	Low	Moderate	High	Very High
Large	Very Low	19.16	3.33	1.07	0.93	0.68
	Low	15.95	12.20	4.13	3.60	3.15
	Moderate	4.92	7.53	2.49	1.96	1.22
	High	2.66	4.76	1.54	1.13	0.63
	Very High	1.75	3.02	0.95	0.71	0.51

Part 2: Technical Report

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Auckland Council

AUCKLAND LANDSLIDE SUSCEPTIBILITY STUDY

TECHNICAL REPORT 2025

28 FEBRUARY 2025




WSP REPORT NO. GS 2025 / 09

AUCKLAND LANDSLIDE SUSCEPTIBILITY STUDY
TECHNICAL REPORT 2025

Auckland Council

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REV	DATE	DETAILS
01	6 June 2024	Draft to Auckland Council and Geotechnical Advisory Panel for comment
02	9 July 2024	Revised report following external peer review
03	10 September 2024	Finalised report
04	28 February 2025	Updated following external peer review

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Approved by:	P Brabhaharan	28 February 2025	Brabhaharan

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GLOSSARY

DEM	Digital Elevation Model
Deposition zone	The area within a landslide where the failure materials accumulate at the base of the slope or where there is a change to a gentler slope.
Factor	A factor refers to a categorical variable, these can be either distinct groups (e.g. geological units) or groups representing ranges of numerical values (e.g. 0-5 m, 5-10 m).
Failure zone	The area within a landslide where the ground detaches and slides outwards towards the free face.
Geomorphic Sub-Region	Areas of land with similar geological and geomorphological characteristics that have been grouped together to define a single area with distinct patterns in the style and distribution of previous landslides. Also referred to as 'Landslide Terrain' in describing landslide characteristics of the region.
GIS	Geographic Information System, a mapping system to manage and analyse spatial data.
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 (AGS, 2007a).
Hillshade	Shaded relief model of topography, generated from a digital elevation model.
Landslide	The movement of a mass of rock, debris, or earth (soil) down a slope.
Landslide inventory	An inventory of the location, classification, volume, activity and date of occurrence of individual landslides in an area.
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 (AGS, 2007a).
Landslide terrain	Areas of land with similar geological and geomorphological characteristics that have been grouped together to define a single area with distinct patterns in the style and distribution of previous landslides.
LiDAR	Light Detection and Ranging, a remote sensing method that uses lasers to measure the earth's surface.
Regression zone	The area behind the head scarp of a landslide where the over-steepened scarp face continues to erode, fail or collapse and regresses over time.
Risk	A measure of the probability and severity of an adverse effect to life, health, property, or the environment.
Scale of landslides	The size of the landslide features relative to the surrounding hillslope. For this study, 'small scale' landslides refer to shallow landslides and debris flows triggered by heavy rainfall events on the sides of hillslopes or within gullies, where the proportion of the affected area of slope is small (these features are typically tens to hundreds of m^2 in area), and 'large scale landslide features' refer to geomorphic features that generally span over most of or the whole hillslope (these features are typically thousands to hundreds of thousands of m^2 in area).
Scale of mapping	The map scale of the variables used in the analysis. This can vary from small scale (e.g., regional geology maps at 1:250,000 scale) to large scale (e.g., shallow landslide mapping in the landslide inventory, carried out at scales of ~1:2,000 to ~1:500).

Scale of assessment and outputs	The map scale of the susceptibility assessment outputs. This study is a regional-scale study, to provide information about the distribution of landslide susceptibility for regional planning purposes. Recommended map scales for the use of the outputs from regional-scale landslide assessments are typically between 1:100,000 and 1:25,000.
Variable	Variables can be classified as either categorical or numerical. Categorical variables take on values that are categories or groups (e.g., geological unit or slope aspect), while numerical variables are measured on a numerical scale (e.g., slope angle or slope height). Variables have also been termed 'susceptibility factors' or 'parameters'.
Zoning	The division of land into areas or domains of broadly similar vulnerability and their ranking according to degrees of actual or potential landslide susceptibility, hazard or risk.

EXECUTIVE SUMMARY

Auckland Council has a strategy to proactively manage the risk from natural hazards and enhance the resilience of the region to such hazards. The Auckland Region includes significant areas of steep terrain that are underlain by materials that can be prone to slope failure, and recent large storms have caused significant and widespread impacts from landsliding. Auckland Council is aiming to improve the understanding and mapping of landslide hazards across the region. This study has been prepared as part of this programme and provides a regional scale assessment of landslide susceptibility consistent with a 'Level A' analysis under the GNS Science (2024) Landslide Planning Guidance (de Vilder et al., 2024).

The methodology of the study aligns with the 'Basic' level assessment described in the Australian Geomechanics Society Guideline for Landslide Susceptibility, Hazard and Risk Zoning (AGS, 2007a). The study area consists of the Auckland regional boundary, including the Hauraki Gulf islands.

In assessing the susceptibility of the region to landslides we have differentiated two key types of landslides: (1) shallow landslides and debris flows, and (2) large-scale, slow-moving or relict landslide features. Consideration and mapping of these two landslide types was carried out separately because they differ considerably in terms of the scale, frequency of occurrence, the type and extent of impacts, and the susceptibility characteristics of the geological formations within the region.

The primary objective of this study is to map areas susceptible to landslides across the Auckland Region for land use planning. To highlight these areas, we have compiled an inventory of previous landslides across the region, identified and assessed variables that influence slope stability, and combined these to develop landslide susceptibility maps. Statistical analysis of the landslide inventory, local site conditions, and professional judgement were used to inform the relative importance of specific variables to landslide susceptibility. This was completed using logistic regression for the shallow landslide susceptibility analysis and heuristic assessment for the large-scale landslide susceptibility.

Five categories of landslide susceptibility are described, from Very Low to Very High, and these are mapped across the region in GIS showing the spatial distribution and extent of the different susceptibility categories. The maps do not present potential areas of regression and runout of landslide debris, as these have not been assessed at this stage. The maps are suitable for use at 1 : 25,000 scale for shallow landslide susceptibility and 1 : 50,000 scale for large-scale landslide susceptibility. The maps should be used at scales appropriate for this regional-scale assessment, and where made available to the public through the Council GIS viewer the scales at which they can be viewed should be restricted.

Recommendations for follow on actions and future enhancements are provided, including review and update of the maps when new data becomes available, refinement of the mapping to a finer resolution, and assessment of regression and runout in areas which could be impacted by landslides. It is also proposed that the maps be used in future land use planning, urban growth strategies and plan change proposals to manage the risks from landslide hazards. The maps could also be useful for the Council's infrastructure departments and should be made available for other government and private infrastructure owners to understand the resilience of the services provided. The maps would also be valuable for planning for civil defence emergency response.

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Auckland Council

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1 PROJECT BACKGROUND

1.1 INTRODUCTION

Auckland Council has a strategy to proactively manage the risk from natural hazards and enhance the resilience of the region to such hazards. The Auckland Region includes significant areas of steep terrain that are underlain by materials that can be prone to slope failure, and recent large storms have caused significant and widespread impacts from landsliding. Auckland Council is aiming to improve the understanding and mapping of landslide hazards across the region. This is part of a wider initiative to better define risks from natural hazards for more effective land use planning and planning decisions, as well as inform the infrastructure recovery after severe storm events impacted the region in early 2023.

Landslide hazards cause significant damage to our built and natural environment, and these hazards are exacerbated by the increased frequency and severity of weather events, considered to be a consequence of climate change. The Auckland Anniversary Storm in January 2023 and Cyclone Gabrielle in February 2023 are recent examples of severe hazard events with widespread landsliding and consequential impacts on the built and natural environment.

WSP has been supporting local authorities in assessing and mapping the susceptibility of slopes to landslides and developing planning measures to manage the risk from these hazards to our society. This assists Aotearoa to be Future Ready and face these increasing challenges by proactively managing the risk from landslide hazards. Brabhaharan (2010) provides information on the different grades of zonation and their application in management of the risk associated with natural hazards.

Auckland Council has commissioned WSP to assess landslide susceptibility across the Auckland Region. This report outlines the methodologies used for assessing and mapping areas susceptible to landslides across the region and presents the results of the study.

1.2 SCOPE AND PURPOSE

The primary objective of this study is to map areas susceptible to landslides across Auckland Region.

The scope of work for this mapping includes the following:

- Collate a landslide inventory for the region from existing information and through additional mapping.
- Undertake an assessment of landslide susceptibility and produce maps indicating areas that have various levels of potential for landslides.

The purpose of this mapping is to:

- Provide information on the distribution of landslide-susceptible areas across the region, so that this can be taken into consideration in proactive land use and infrastructure planning.
- Facilitate the development of district planning regulations to allow proactive management of the risks associated with development.
- Enable the risks from landslide hazards and the resilience of infrastructure to be better understood, to allow planning of mitigation measures.

1.3 STUDY AREA

The study area comprises the Tāmaki Makaurau / Auckland Region which is in the upper North Island Te Ika-a-Māui (Figure 1). This includes central Auckland City and the surrounding areas including Awhitu Peninsula, Kaipara Peninsula, Muriwai, Waitakere Ranges, Hunua Ranges, Waiheke Island, and the Hauraki Gulf Islands (Great Barrier and Little Barrier).

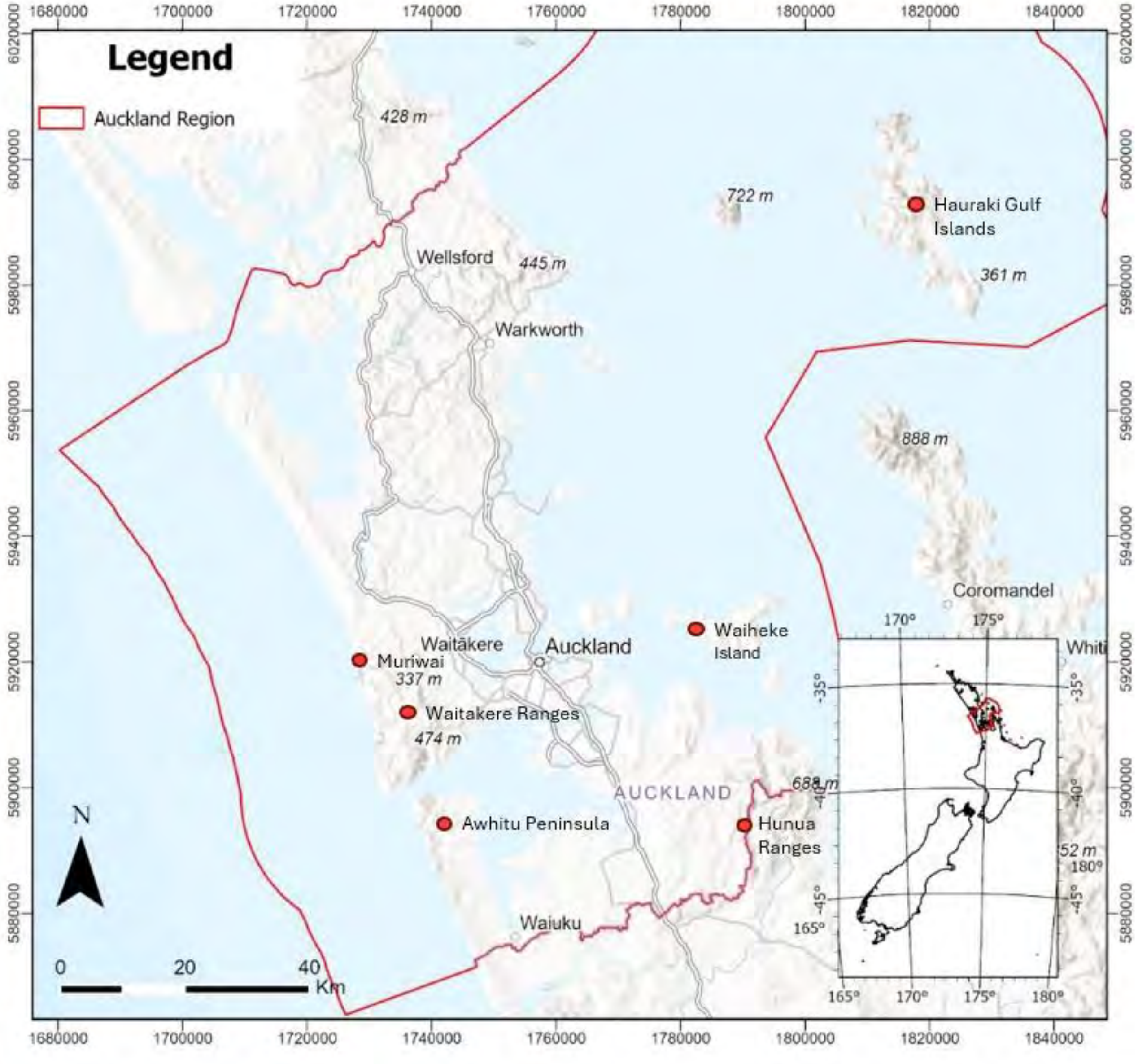

Figure 1: Map of the Auckland Region, with the study area outline highlighted in red. Inset showing location of study area within New Zealand

2 STUDY METHODOLOGY

2.1 OVERVIEW

The primary objective of this study is to identify areas susceptible to landslides across the Auckland Region for land use planning. This corresponds to a 'Level A' analysis under the GNS Science (2024) 'Landslide planning guidance: reducing landslide risk through land-use planning' (de Vilder et al., 2024). To highlight these areas, we have compiled a landslide inventory for the region, identified and assessed variables that influence regional slope stability, and combined these to develop landslide susceptibility maps. The landslide susceptibility variables were weighted based on our assessment of landslides in the region, for both shallow smaller-scale and large-scale landslide processes, and were calibrated based on available landslide data and local geological knowledge.

The landslide landslide susceptibility analysis and mapping methodology has been prepared using the 2007 Australian Geomechanics Society 'Guideline for landslide susceptibility, hazard and risk zoning for land use planning' (AGS, 2007a). Key terms and definitions defined by AGS (2007a) are reproduced in Table 1.

Table 1: Key landslide susceptibility mapping terminology from AGS (2007a).

Term	Definition
Landslide	The movement of a mass of rock, debris, earth or soil down a slope.
Landslide Inventory	An inventory of the location, classification, volume, activity, date of occurrence and other characteristics of landslides in an area
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.
Landslide Susceptibility Zoning	The division of land into homogeneous areas or domains and their ranking according to degrees of actual or potential landslide susceptibility.

Under AGS (2007a), landslide susceptibility zoning addresses the classification, volume (or area) and spatial distribution of existing and potential landslides in the study area. Three levels of assessment ('Basic', 'Intermediate' and 'Sophisticated') are defined in the guideline, which are determined by the quality and availability of input data and the required usage and scale of the output maps.

Landslide inventory compilation and geomorphologic mapping are prerequisite steps to landslide susceptibility zoning. The level of assessment used for these initial stages needs to be consistent with the level to be used for the susceptibility zoning. The landslide inventory compiled for this study aligns with the 'Basic' level of AGS (2007a), as it includes the location of the landslides in GIS format but contains little detail on the classification or volumes of the landslides, and few dates of occurrence (see Section 5). Based on this and given the scale of the other geospatial datasets that cover the whole region available for use in the assessment, the susceptibility assessment generally aligns with the 'Basic' level of assessment, which is appropriate for a regional-scale study. The activities recommended for basic landslide susceptibility zoning include geomorphological mapping, landslide inventory compilation, assessment of the spatial frequency of landslides with correlation to factors such as geology, slope, climate etc., and preparation of a landslide susceptibility map.

2.2 ASSESSMENT OF DIFFERENT LANDSLIDE TYPES

In assessing the susceptibility of the region to landslides we have differentiated two key types of landslides:

- Shallow landslides and debris flows, and
- Large-scale, slow-moving or relict landslides.

These are referred to as *'shallow landslides'* and '*large-scale landslides*' throughout the remainder of the report.

'Shallow landslides' tend to be small, slope-scale failures within the shallow near-surface soil and rock materials where the proportion of the affected area of slope is small (these features are typically tens to hundreds of m^2 in area, and generally less than 5 m deep (Hungr et al., 2014)). These typically occur on the sides of hillslopes or gullies where steep slopes, concentration of overland flow paths, and accumulations of soil or weak bedrock combine to cause failure of the surficial materials. These failures are triggered by prolonged or intense rainfall events and are generally rapid (>1.8 m/h) to extremely rapid (>5 m/s) (Hungr, Leroueil, & Picarelli, 2014).

'Large-scale landslides' are observed as geomorphic features that generally span over most of or the whole hillslope (these features are typically thousands to hundreds of thousands of m^2 in area). These are related to deeper geological structures and groundwater conditions, and other longer-term landscape-scale processes such as tectonic uplift and fluvial incision (particularly toe erosion causing de-buttressing of susceptible hillslopes), and volcanic or earthquake activity. The age and longevity of these features in the landscape is significantly longer than the shallow landslides (i.e., on timescales of tens to hundreds or thousands of years, or more).

Consideration and mapping of these two landslide types was carried out separately because they differ considerably in terms of their scale, the frequency of occurrence, the type and extent of impacts, and the susceptibility characteristics of the geological formations within the region. As a consequence, the level of hazard, land use responses and the type and cost of potential mitigation strategies will vary. By considering and mapping these separately, appropriate planning responses can be developed for them based on their characteristics.

The characteristics of these landslide types are discussed in Section 4 and the approaches for identifying and capturing these in the landslide inventory mapping are described in Section 5.

2.3 DESKTOP APPRAISAL

A desktop review of available data, reports and research papers was undertaken to:

a) Understand the geological and geomorphic characteristics of the region.

b) Understand where landslides have previously occurred in the study area.

c) Create a list of variables reported to affect slope stability in the region.

d) Create a list of typical landslide failure mechanisms in the region and similar environments.

The desktop study focused on identifying the key variables that influence landslide susceptibility in the region, in the context of the particular geological and geomorphic settings within the region. To identify potential landslide susceptibility variables, we completed a literature review of landslides in the Auckland Region including a review of regional geology and geomorphology, previous studies, landslide occurrence, hazard zones, typical mechanisms, and implications for the built environment.

This included the following data sources:

- Reports on landslides and slope stability within the region, including collation of landslide data from Council records, mapped landslides from GNS Science and the NZ Landslide Database, and relevant landslide and geotechnical reports from WSP's project database.
- Documented storm events that have caused significant landslides (e.g. 2008, 2017, and 2023), supplemented by WSP's experience in responding to numerous storm events in Auckland and throughout Aotearoa New Zealand.
- International literature on landslides, with particular focus on rainfall-induced landslides in flysch sequences (soft sedimentary rock sequence), volcanic terrain, and basement terrain.

Table 2: Summary of geological and landslide studies reviewed as part of this study.

Usage	References
Regional Geology/Geomorphology	Bland et al., 2023; Hayward, 2011; Edbrooke et al., 2002; Edbrooke et al., 2003; GNS Science, 2020; Hayward, 2017; Kermode, 1992; Moon & Healy, 1994; Moon & de Lange, 2010; Searle, 1964
Landslide occurrence	Brooke, 2024; Hancox & Nelis, 2009; Lee, 2020; Wilson et al., 2023; Wright, et al., 2009
Previous landslide studies	Amora, 2015; Bloom, 2022; Williams, 1996
Implications for the built environment	George & East, 2001; Winkler, 2003

2.4 SITE RECONNAISSANCE

Site reconnaissance inspections were carried out in August 2023 and March 2024 by engineering geologists and geotechnical engineers from WSP and Auckland Council. These consisted of drive over inspections of publicly accessible landslides, and helicopter reconnaissance from Whitford to Warkworth and Muriwai to Manukau Heads, as shown in Figure 2. The purpose of the early reconnaissance was to inspect the failed slopes in different geological areas, to understand the failure mechanisms for selecting appropriate susceptibility factors. The 2024 reconnaissance was to help verify that the geospatial analyses were providing reliable results, and to explore the issue of terrains affected by large scale landslides, and the geomorphic characteristics of these large features.

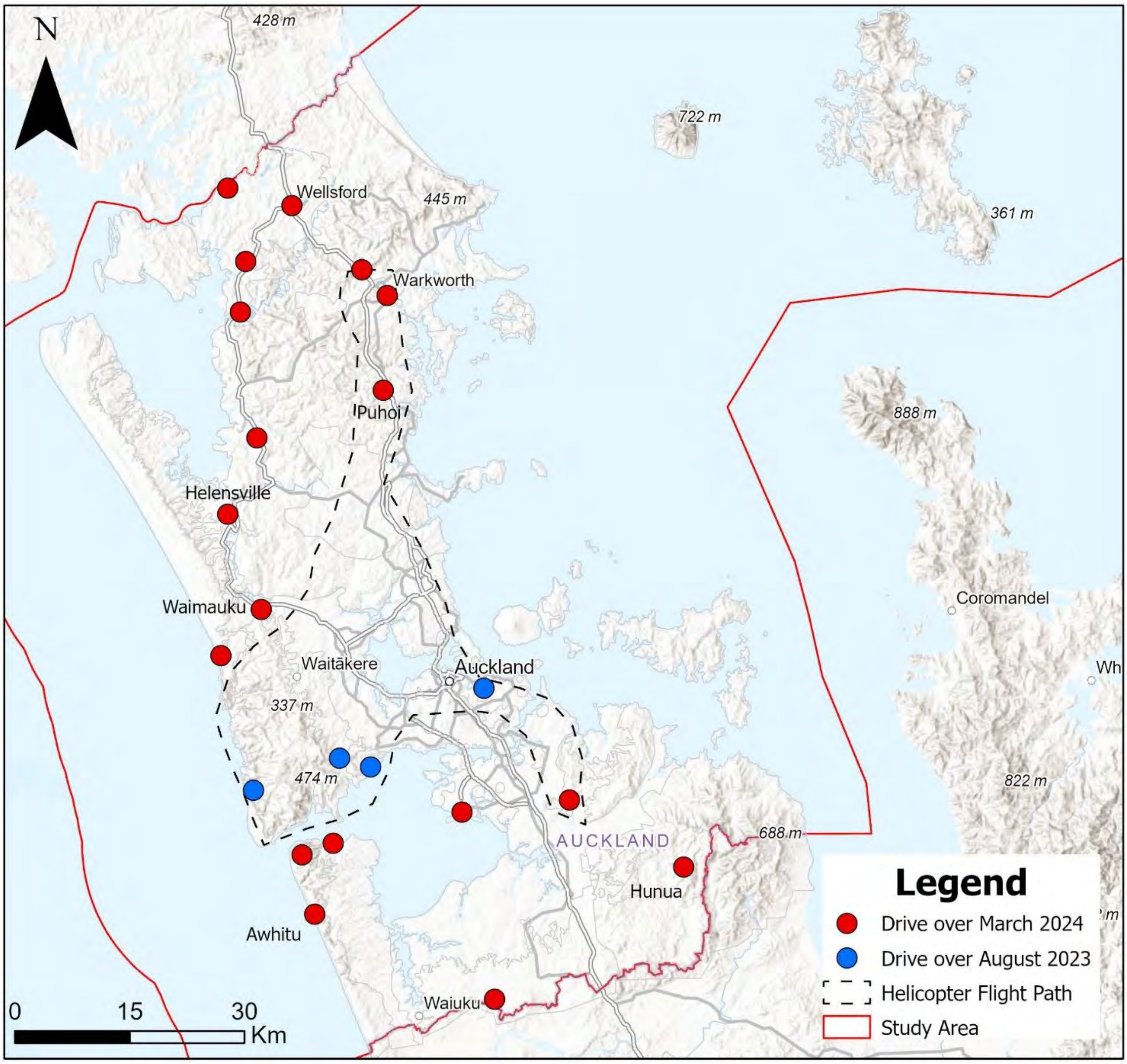

Figure 2: Map of areas visited during the site reconnaissance visits

2.5 LANDSLIDE INVENTORY PREPARATION

Preparation of a landslide inventory is essential for assessment of landslide susceptibility (AGS, 2007a). Separate landslide inventories were compiled in this study, for 'shallow small-scale' and 'large-scale' landslides, as these were determined to be the two dominant landslide types in the region that required separate evaluation approaches to assess landslide susceptibility.

Preparation of these landslide inventories involved collation of existing published and unpublished datasets in GIS, supplemented with specific landslide mapping by WSP geologists. The landslide mapping was carried out in ArcGIS using a variety of geospatial layers including satellite imagery, topographical data, and geological maps. Each landslide in the inventory was described following existing methodologies (e.g. Varnes, 1978; Hunger et al. 2014; Cruden & Couture, 2011).

2.6 VARIABLES INFLUENCING LANDSLIDE SUSCEPTIBILITY

A previous regional landslide susceptibility investigation (Williams, 1996), considered variables such as geology, slope angle and previously known areas of instability. A range of variables have been identified and used for previous landslide susceptibility mapping in New Zealand, such as for Wellington, Hutt City, Tauranga and Bay of Plenty (Brabhaharan et al., 1994; WSP, 2021; WSP, 2023; WSP, 2024). Corominas et al. (2014) provide an overview of variables controlling the occurrence of landslides for use in landslide susceptibility and hazard assessment. For this study, not every variable identified as of high importance by Corominas et al. (2014) was able to be used, due to a lack of data availability for the whole region or relevance to the landslide terrains being assessed.

The variables used in the assessment of both shallow smaller scale landslides and large-scale landslide features are described in Table 3. These variables represent particular characteristics of the region (such as slope angle or geological unit) that are proxies for the physical processes that contribute to landslides. GIS layers for each variable were sourced from published datasets and collated in a GIS database. The source of the data, its original scale (or resolution), and the processing or filtering methods applied to the GIS datasets for the landslide susceptibility analyses are described for each variable in Sections 6 and 7 of this report.

Generally, variables influencing landslides used in both the shallow and large-scale susceptibility assessments are similar, however, there are subtle differences in how they were utilised due to the different characteristics of each landslide type. These differences are due to the mapped large-scale landslide features encompassing a range of more complex geomorphic processes, and therefore some of the variables selected for the smaller scale landslide mapping are not applicable to the large-scale landslide susceptibility assessment. For example, the geomorphon factor (for definition see Table 3 below) was not used in the large-scale landslide susceptibility assessment, due to the tendency of landslides to span multiple geomorphon classes and therefore they do not closely correlate to a specific geomorphon type.

Table 3: Landslide susceptibility variables considered in this study and their usage in the shallow and large-scale landslide susceptibility assessments.

Category	Variable	Variable description and influence on landslide susceptibility	Where used in landslide susceptibility assessment	
			Shallow	Large scale
Geomorphology	Slope angle	Angle of slope within each grid cell, calculated using LiDAR DEM supplied by Auckland Council. Steeper slopes generally correspond to higher susceptibility to landslides	✓ (Table 9)	✓ (Table 20)
	Local slope relief	Elevation difference indicating topographic variation, calculated from LiDAR DEM supplied by Auckland Council. This factor represents the local height and angle of the slope surrounding each grid cell in the elevation dataset (i.e. the broader steepness rather than just the slope angle of each cell). It is calculated by comparing the difference in elevation between the cells within a given radius of the selected cell. Higher, steeper slopes are generally more susceptible to failure. Slope height also influences the size and runout of landslides.	✓ (Table 9)	✓ (Table 22)
	Aspect	The compass direction in which a slope faces, calculated from LiDAR DEM supplied by Auckland Council. The aspect of a hillslope can directly influence the slope's stability through exposure to sun, prevailing wind and rainfall. Indirect influences of slope aspect on stability include variability of vegetation cover and soil moisture.	✓ (Table 9)	✓ (Table 21)
	Slope profile curvature	The curvature (convex, flat, or concave) of a slope influences the flow of water across it, and the concentration of flows, which can in turn influence slope stability. This can also represent weaker materials or presence of soils, reworked or extremely weak rock. These can influence the susceptibility to landslides. Curvature was calculated using LiDAR DEM supplied by Auckland Council.	✓ (Table 9)	
	Landform (geomorphon)	The geomorphon landforms tool in ArcGIS provides a representation of the position of each grid cell within the landscape based on the patterns of elevation difference amongst the surrounding cells. The topographic position of each landform can influence its susceptibility to landslides, with landslides commonly observed in the middle and upper parts of hillslopes.	✓ (Table 9)	
Geology	Geology	The lithologies of slope materials have different shear strength, rock mass strength, moisture sensitivity and permeability characteristics, which influence the vulnerability of the slope to failure, erosion and weathering. Weaker, unconsolidated materials are generally more susceptible to instability than strong consolidated soil or rock. GNS QMAP used as input layer.	✓ (Table 10)	✓ (Table 18)
	Geomorphic sub-region	Study area classified based on similar geological formations, geomorphic landforms and processes.	✓	✓ (Table 18)
	Geological structure	Relationship of slope geometry to geological structure (bedding, fault planes etc.). Slopes with persistent geological discontinuities such as bedding or fault planes that are adversely oriented with respect to the hillslope direction will be more susceptible to large scale landslides.		✓ (Table 19)

Category	Variable	Variable description and influence on landslide susceptibility	Where used in landslide susceptibility assessment	
			Shallow	Large scale
Hydrology	Distance to stream	Slopes located close to streams are likely to have shallower groundwater levels and may be undercut and over-steepened (destabilised) by scour or erosion at the toe of the slope. Calculated using LINZ river datasets.	✓ (Table 11)	✓ (Table 23)
	Distance to overland flow path	Slopes located close to overland flow paths are likely to have shallower groundwater levels and concentrated runoff and infiltration during storm events. These areas may also be undercut and over-steepened (destabilised) by scour or erosion during high flows. Calculated from overland flow path dataset supplied by Auckland Council.	✓ (Table 11)	
Land cover	Land cover	The type of land cover can affect the susceptibility of a slope to instability by influencing the rates of surface water runoff, infiltration, and erosion. Sparsely vegetated slopes are generally considered to be more susceptible to slope instability. The presence of root systems can improve stability. LRIS land cover database v5.0 used as input layer.	✓ (Table 12)	
Landslide Inventory	Landslide	Previous landslides on a slope indicate the potential for further slope instability. A regional landslide inventory was compiled from existing information sources as well as additional landslide mapping carried out for this project. See Section 5 for description of the inventory.	✓ (Table 13)	✓ (Table 24)

2.7 LANDSLIDE SUSCEPTIBILITY ASSESSMENT

Landslide susceptibility in this study was assessed for the region for two distinct landslide types:

1) Shallow, smaller scale landslides, and
2) Large-scale landslide features.

Two different methodologies were used to assess susceptibility for each landslide type. These methodologies followed the same principles of analysing potential landslide-inducing variables and assessing land susceptibility based on local conditions and considering the inventory of landslides mapped. Statistical analysis of the landslide inventory, local site conditions, and professional judgement were used to inform the relative importance of specific variables to landslide susceptibility. This was completed using LASSO (Least Absolute Shrinkage Selection Operator) penalised logistic regression (Meier, van de Geer, & Buhlmann, 2008) for the shallow landslide susceptibility analysis, and Analytical Hierarchy Process (AHP) (Goepel, 2018; Saaty, 1980) for the large-scale landslide susceptibility.

Analysis of the landslide inventory identified susceptibility variables that potentially influence landslide occurrence and their relative importance. Using the developed methodologies for each landslide type, the available datasets for the variables were analysed and the Auckland Region was assessed in terms of its susceptibility to landslides. The results were divided into 5 classes (Very Low, Low, Medium, High, and Very High) for displaying the landslide susceptibility on maps.

Two susceptibility maps have been produced for the region, one for each landslide type considered. Sections 6 and 7 in this report outline the detailed methodology used for the landslide susceptibility analyses and the classification of susceptibility descriptors.

It is important to note that landslide susceptibility mapping does not quantify the number of landslides which may occur in a given event or time period, nor the annual probability of landslides occurring, as these are outputs of hazard mapping (Fell, et al., 2008).

3 REGIONAL SETTING

3.1 GEOLOGY AND GEOMORPHOLOGY

The Auckland Region is a geologically young and active landscape, shaped by tectonism, deep sea basin development and volcanism driven by processes associated with the Pacific and Indo-Australian plate boundary along which New Zealand is located (Edbrooke et al., 2003; Hayward et al., 2017). The geological history of the region and the principal geological formations are summarised below, from oldest to youngest.

The Auckland Region's basement greywacke rocks of the Waipapa Terrane dip down to the west and are only exposed in eastern areas such as the Hunua Ranges and Hauraki Gulf Islands (e.g., Waiheke Island). The greywacke rocks are buried beneath younger units throughout the middle and western areas of the region.

The Northland Allochthon was emplaced into the Northland and Auckland Regions during the early to mid-Miocene as a series of thrust sheets of oceanic sediments and crustal materials. Units of the Northland Allochthon were subsequently incorporated within the sediments of the Waitemata Group that were deposited in the Waitemata Basin. The sediments in the Waitemata Basin include eroded material from the Northland Allochthon units and volcanic material from volcanoes to the west. These sediments were deposited as debris flows and turbidity currents into the Waitemata Basin, unconformably over the greywacke building a thick sequence of sandstone and mudstone rocks (flysch). Subsequent uplift and erosion of these rocks has formed the cliffs exposed in the East Coast Bays and Waitemata Harbour areas. The uplift and faulting of the Waitemata Group sediments have also formed the northern hills north of Warkworth and the southern landslide zone hills near Whitford (Hayward, 2017).

Volcanism associated with the collision of the Australian and Pacific plates during the Miocene (Hayward, 2011) has resulted in the formation of steep ranges in the west comprised of volcaniclastic rocks. More recently from the Pleistocene into the Holocene saw eruptions of basaltic volcanic fields in South Auckland and Auckland forming discrete volcanic scoria cones and explosion tuff craters with associated volcaniclastic deposits, including lava flows, lithic tuff, lapilli, and volcanic ash across the central and southern parts of Auckland (Searle, 1964).

During the Pliocene and Pleistocene periods, alluvium was deposited across coastal, marine and river environments, and the Awhitu Group Barrier dune sequences developed along the western flanks of the Auckland Region (Hayward, 2017).

The types of landslides that occur in the different terrains are strongly linked to both the geomorphic processes and the underlying geology. Therefore, we have characterised the geology and geomorphology of the region into a series of sub-regions or landslide terrains for the purposes of assessing and classifying landslide susceptibility. The geomorphic sub-regions were derived using terrain data, geological mapping, and available information on geomorphic features and landslide types across the region. The integrated geological and geomorphic sub-regions are summarised in Table 4 and shown in Figure 3 (after Edbrooke et al. 2002).

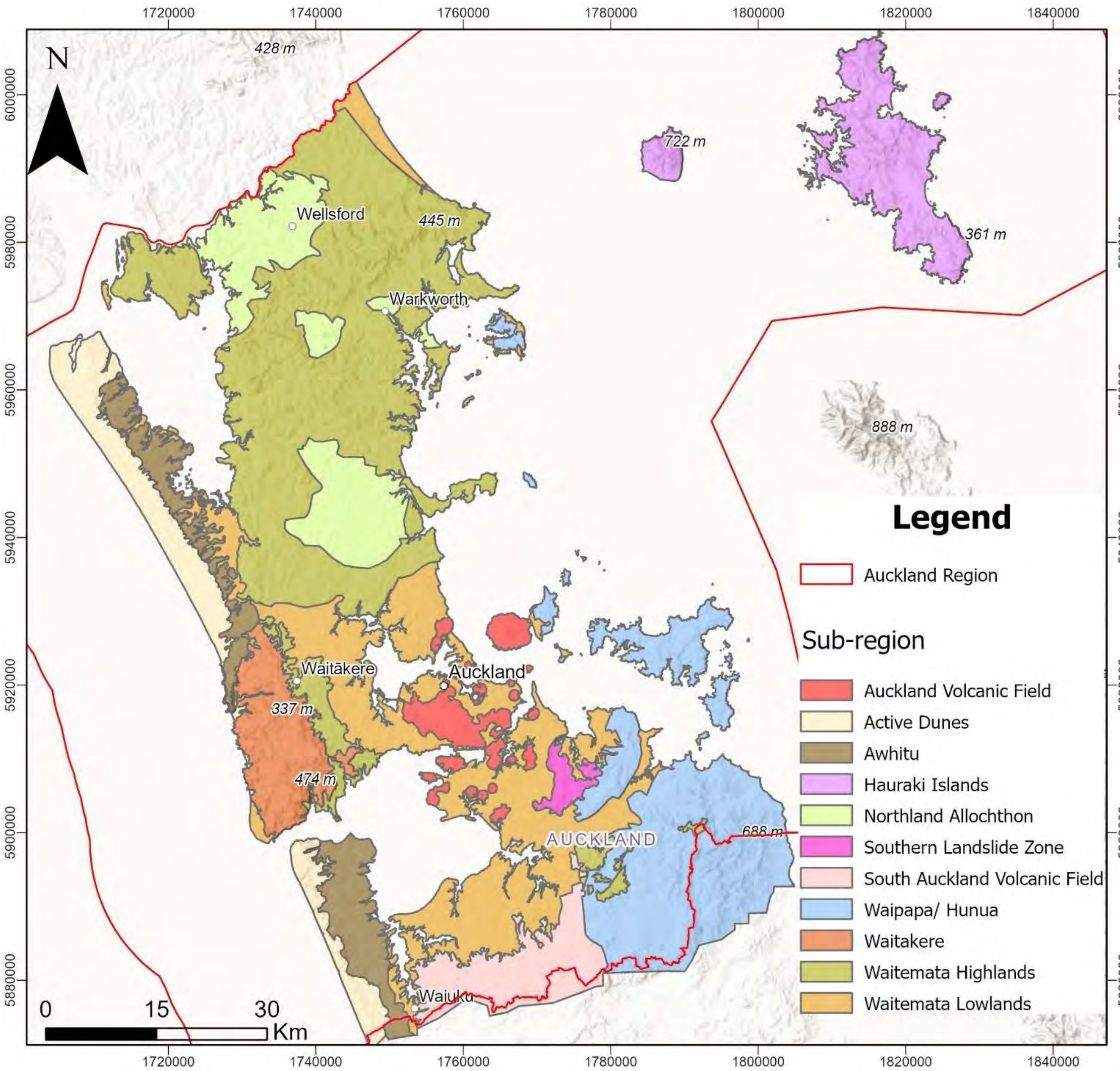

Figure 3: Map of the Auckland Region characterised into 11 geomorphic sub-regions adapted from (Edbrooke et al, 2002).

Table 4: General description of each geomorphological sub-region.

Geomorphic sub-region	Generalised landslides, geological, and geomorphological characteristics
Active Dunes / Early Pleistocene parabolic dunes	Active Dunes have soil flows. Early Pleistocene Parabolic Dunes have loose to poorly cemented, quartzofeldspathic and mafic-rich sands in fixed parabolic dunes and local, small transverse dunes. Early Pleistocene Parabolic Dunes are weakly cemented and uncemented quartzofeldspathic to mafic-rich, dune-bedded sand and clay-rich sandy paleosols, with lenses of carbonaceous mudstone, muddy sandstone, and lignite.
Awhitu Group	Awhitu Group landslides display brittle behaviour with rapid strength loss and transition into soil flows. Hill slopes are usually long, with closely spaced first order drainage channels formed by translational landslides that transition to fluidized flows associated with high groundwater. Moderately to poorly cemented large-scale cross-bedded dunes.
Auckland Volcanic Field	Shallow regolith slumps and flows in ash soils and weathered tuff. Differentiated lava flows, volcanic cones and explosive tuff rings and craters, with areas of thick overlying volcanic ash tephra. Rock and soil properties are highly variable depending on the primary materials and degree of weathering.
Hauraki Islands	Localised landslides where weak hydrothermally altered rock occurs and where weathered soils occur on steep slopes. Hydrothermally altered volcanic and volcaniclastic deposits of the Coromandel Group occur in places on Little Barrier and Great Barrier Island. Landscape consisting of close-set, steep sided valleys.
Northland Allochthon	Large-scale areas of creep-type slope deformation are prevalent in low strength mudstone rock masses. Rock mass strength is generally low due to a highly sheared, chaotic, and fractured rock fabric. The intact mudstone material is generally extremely weak to weak. Some Northland Allochthon contains areas of carbonate rock which is not closely sheared and behaves differently to the rest of the unit. Hummocky terrain with low relief, localised high groundwater levels and landslides with springs.
Southern Landslide Zone	Large-scale landslides occur that are controlled by bedding-parallel clay seams. The area is characterised by numerous historic deep-seated block slides and recent shallow landslides. Landslides occur that are controlled by geological structure and terrain, with landslides observed where bedding-parallel clay seams daylight within incised stream valleys. Medium to high relief with terracettes, and with drainage gullies leading down to streams.
South Auckland Volcanic Field	Slumping can occur in over-steepened areas. Variably weathered basalt, localised tuff rings and volcanic lithic tuff, unconsolidated ash, and lapilli deposits. Moderately flat terrain, with areas of rolling hills and localised volcanic cones rising above the hills.
Waipapa / Hunua	Greywacke rock masses are typified by closely spaced and short-persistence joints which result in rock mass and regolith failures along irregular paths of discontinuous joints. Moderately steep terrain, consisting of close-set, steep sided valleys. Predominantly comprised of indurated, grey, quartzofeldspathic thin- to medium-bedded sandstone and mudstone, and very thick-bedded sandstone.
Waitakere	Slope movement is associated with defect-controlled fall of large semi-intact blocks and rockfall from cliffs and bluffs and soil flows from weathered soils on moderately steep slopes. Volcaniclastic conglomerates and sandstones of the Waitakere Ranges and Piha-Karekare. Steep hills and bluffs.

Geomorphic sub-region	Generalised landslides, geological, and geomorphological characteristics
Waitemata Lowlands	Localised slumping. Auckland Region lowland areas are characterised by shallow meandering drainage gullies, streams, and rivers edges; localised with incised channels. Floodplain (alluvial), lacustrine and coastal deposits.
Waitemata Highlands	Shallow failures and deeper defect-controlled slide blocks. Generally, sandstones volcanic rich and marine-deposited turbidites, forming interbedded sandstone and mudstone. Steep and typically incised drainage gullies with localised steep slopes. Generally, cliff slopes less than 20 m high.

3.1.1 ACTIVE DUNES / EARLY PLEISTOCENE PARABOLIC DUNES

The west coast of Auckland protects the Manukau and South Kaipara Harbours due to the recent active dune and cemented relic sand dune deposits of the Awhitu and South Kaipara peninsulas (Figure 4).

The active dunes are described as loose to poorly cemented, quartzofeldspathic and mafic-rich sands in fixed parabolic dunes and local, small transverse dunes.

Figure 4: Examples showing the range of geomorphic settings within the Active Dunes and Early Parabolic Dunes

3.1.2 AWHITU GROUP CEMENTED SANDS

The cemented sand dunes of Awhitu peninsular date to the early Pleistocene and are known as the interdune facies of the Awhitu Group. Most of the Awhitu peninsular is dominated by this unit, with sections of the Awhitu Group cemented sand dunes also present further north covering most of Muriwai. They are comprised of mostly steep sided gullies, with scoop shaped hollows and small, local transverse dune ridges. These formations were originally deposited as parabolic dunes during the early Pleistocene and have since become cemented by the presence of iron minerals precipitated out of solution from groundwater. Harder layers (hard pans) are typical throughout the sequence.

The lithofacies of this formation are typically moderately to poorly consolidated, large-scale cross-bedded quartzofeldspathic to quartzose dune sand. Some minor parallel and ripple laminated sandstone is present with paleosols, lignite and carbonaceous mudstone. The sands are mafic rich with conglomerate, tephra, rhyolitic ignimbrite, and rhyolitic tephra being present locally (Hayward, 2017).

Failures typically observed within the Awhitu Group cemented sands are brittle slumps that transform into soil flows. Hillslopes are usually long and linear, with closely spaced first order channels formed by translational landslides that transition to fluidised flows with groundwater influence (Figure 5). The Awhitu Group unit is commonly truncated by erosion on the West Coast region due to the coastal margin influence, which is seen on Awhitu Peninsular at Orua Bay in Muriwai.

Figure 5: Examples showing the range of geomorphic settings within the Awhitu Cemented Sands

3.1.3 AUCKLAND VOLCANIC FIELD

Volcanic landforms are one of the many features in Auckland City (and, naturally, the underlying materials) are volcanic in origin. Their geological, geomorphological, and geotechnical properties are outlined below, with examples shown in Figure 6.

Auckland volcanic field extends across the Auckland city urban areas and islands and consists of at least 50 eruption centres (Hayward, 2011). Eruptions typically began with an explosive phreatomagmatic phase forming a crater and surrounding low height tuff ring. If the supply of magma ceased at that point, then the resulting feature was an explosion crater, typically infilled with water to form a lake, that could become breached and drained or flooded by sea level rise. If magma continued to be supplied to the eruption, then eventually groundwater feeding the explosive phreatomagmatic phase would become depleted and the eruption would transition to fire fountaining, the process that forms scoria cones. If eruptions continued, then the development of lava flows would occur. Landforms associated with volcanic activity include explosion craters and tuff rings that formed lakes and maars, scoria cones and shield volcanoes, and lava flows forming lava fields, ridges and offshore reefs (Searle, 1964).

Scoria cones consist of moderately steep hillslopes, commonly prone to debris flows from overland flow and scouring as well as regolith slumps and soil flows on steeper slopes. Basalt lava consists of strong to very strong intact strength rock with closely to widely spaced joints and are associated with moderately steep to steep hillslopes (Searle, 1964). Cut slopes formed in the lava units are susceptible to rock fall and toppling. The rock mass typically is very strong to weak, depending on the degree of welding, with closely to widely spaced joints, and variable weathering.

Figure 6: Examples showing the range of geomorphic settings within the Auckland Volcanic Field

3.1.4 NORTHLAND ALLOCHTHON

Large areas of Northland Allochthon are exposed in the northernmost area of the Auckland Region and outcrops in areas such as Wellsford and Mangakura to the west and Warkworth and Snells beach to the east. The Northland Allochthon has a highly sheared and fractured, chaotic structure, with a weak-moderately strong intact material strength but low rock mass strength. The materials range from weak calcareous and non-calcareous mudstone to weak to moderately strong fine-grained limestone and massifs of displaced volcanics.

The allochthonous landforms are expressed geomorphically as low-lying hills, that are associated with hummocky terrain and low relief. High groundwater levels are found associated with landslide features that can be identified by the presence of localised springs.

The issues the Northland Allochthon pose for landslides are significant (George & East, 2001). Typically, two types of failure occur within the geology: natural slope failure and cut slope failure. Large-scale slow moving natural landslides are prevalent. Graben-style terracettes can occur below the head scarp area, which is part of the ongoing “slope flattening” process. Natural slope failures develop as ongoing intermittent failures, often discreetly bulging at the toe downslope forming mounds (Hayward, 2017).

Natural failures are typically driven by groundwater. Cut slopes in contrast can fail on excavation due to stress release in the sheared rock mass resulting in dilation and ravelling of the material upslope. Cut slopes associated with roading and building development in north Auckland typically require active management measures to prevent the slip regressing upslope.

Natural slopes are typically undulating to gentle. The sheared mudstones are rich in clays, and in the presence of groundwater the clays readily lubricate the movement of landslides.

Figure 7: Examples of geomorphic settings within the Northland Allochthon

3.1.5 SOUTHERN LANDSLIDE ZONE

The Southern Landslide Zone is situated in the southeastern part of the Auckland Region, east of Manukau, so named because of the numerous historic landslide features that have been mapped in this area. The local topography is typically comprised of moderately steep, rolling hills (Figure 8).

The geology of the Southern Landslide Zone consists of East Coast Bays Formation. The landslide types present here include rotational slumps, translational block slides as well as composite complex landslides, earth and debris flows, debris slides, and tunnel gully erosion. Intense rainfall events often trigger landslides. Many block slides in this area are interpreted to be caused by the presence of bedding-parallel clay seams that formed due to flexural shearing between adjacent beds of sandstone and mudstone rock as a result of regional tectonic folding.

Figure 8: Examples showing the range of geomorphic settings within the Southern Landslide Zone

3.1.6 SOUTH AUCKLAND VOLCANIC FIELD

The South Auckland Volcanic Field spans from Pukekiwiriki east of Papakura in the north to Pukekawa in the south. Consisting of at least 82 volcanoes, the field is older than the Auckland Volcanic Field to the north and has subsequently undergone deeper weathering and more erosion.

The South Auckland Volcanic Field is moderately flat, with rolling hills. Eroded remnants of scoria cones and lava flows occur in the north-eastern areas of the South Auckland Volcanic Field, some of which outcrop in the Hunua Ranges. The southern areas consist of well-preserved scoria cones formed on the low-lying land of the Pukekohe area.

The South Auckland Volcanic Field includes materials comprised of extensively weathered basalt, lithic tuff, unconsolidated ash, and lapilli deposits, which today form fertile soils up to several metres thick. Lava flows are fine to medium grained, vesicular, and porphyritic with ultramafic xenoliths and common quartz (Hayward, 2017).

Slumping can occur in over steepened slopes comprised of scoria and loose accumulations of moderate to hard basalt fragments mixed in with highly weathered basalt.

Figure 9: Typical geomorphic settings in the South Auckland Volcanic field.

3.1.7 HAURAKI GULF ISLANDS

For the landslide terrain classification, the Hauraki Gulf Islands comprise a grouping of two islands with similar geological and geomorphological features; Great Barrier and Little Barrier Islands are in the northeastern corner of the Hauraki Gulf. They are north of the Coromandel Peninsula. The surface of Great Barrier is rugged with rocky bluffs and steep slopes with close-set incised valleys much like the Hunua Ranges. The rocks can be hydrothermally altered volcanic and volcaniclastic deposits (Hayward, 2017).

The Hauraki Gulf Islands are prone to localised landslides during heavy rainfall events, where weak hydrothermally altered rock occurs on steep slopes. The hill slopes are usually long due to the high relief. The landslides are typically shallow soil flows, within gullies and on steep hillslopes with rock topples and rock falls from very steep bluffs. Large-scale landslides can also occur within the Hauraki Gulf Islands.

Figure 10: Examples showing the range of geomorphic settings within the Hauraki Gulf Islands

3.1.8 WAIPAPA / HUNUA

Waipapa Terrane Greywacke forms the basement rocks exposed in the Hunua Ranges and some of the inshore islands in the Hauraki Gulf (Waiheke Island, Kawau Island, Tiritiri Matangi Island, Rakino Island, Motutapu Island, Motuihe Island, Ponui Island, Pakihi Island and Rotoroa Island) to the east of the Auckland Region.

The Hunua Ranges are the fault-bounded, tilted remnants of mountain ranges resulting in sharp ridgelines, high-standing steep slopes comprising close-set, incised steep sided valleys.

The Waipapa Terrane is comprised of thin-bedded alternating fine-grained sandstone and argillite, which is massive, poorly bedded or laminated. There is also massive, jointed greywacke sandstone present in which beds can be tens of metres thick. The presence of zeolites within the greywacke units can contribute to instability when weathered. Some minor rock types of the Waipapa Terrane also include chert; coloured siliceous argillite and green spilitised basalt.

The Hunua Rocks are extremely strong to strong when unweathered. The rock can become more prone to weathering and failure along bedding between sandstone and argillite, and where there are joints and fractures in the rock mass. These rocks are more prone to failure where the strata dips towards the free face, as can occur in road cuttings or incised river valleys.

Landslides observed within the unit include shallow scallop-like regolith failures, and shallow debris flows and soil flows.

Figure 11: Examples showing the range of geomorphic settings within the Hunua Ranges and Waiheke Island.

3.1.9 WAITAKERE RANGES

Located west of Auckland, the Waitakere Ranges are the eroded remnants forming the eastern flanks of the now buried Waitakere Volcano and are 16 million years old. During a period of uplifting and tilting, the ranges tilted to the northwest.

The Waitakere Ranges are an area of elevated hills, ranges and coastal landforms defined by topography that is steeper in the west, with high standing bluffs, and characterised by rolling hills to the east (Edbrooke et al. 2003).

The Waitakere Ranges are dominated by the Piha Formation and Nihotupu Formation of the Waitakere Group.

The Piha Formation is comprised of coarse volcaniclastic conglomerates, while the Nihotupu Formation is finer grained volcaniclastic sandstone and mudstone.

The Waitakere Ranges are generally competent and stable, with most slope movements being associated with rockfall from cliffs and bluffs and soil flows from weathered soils on moderately steep slopes.

Figure 12: Examples showing the range of geomorphic settings within the Waitakere Ranges

3.1.10 WAITEMATA GROUP AND PLEISTOCENE TO HOLOCENE DEPOSITS

For the purposes of this study, the Waitemata Group has been split into Waitemata Lowlands and Waitemata Highlands.

The Waitemata Lowlands also includes various Pleistocene to Holocene Age sedimentary deposits including the Takanini Formation that forms extensive lowland areas as well as low height rolling terrain that can terminate at coastal cliffs, comprising the East Coast Bays Formation with variable volcanic content of the Waitemata Group. The Waitemata Highlands typically includes Waitemata Group units such as volcanic rich Pakiri Formation, Helensville Conglomerate, and Cornwallis Formation forming steeper terrain to the north of Auckland City. The Waitemata lowland and highlands areas have been split considering the differing geomorphic terrain affecting the likelihood of landsliding.

3.1.10.1 WAITEMATA LOWLANDS

Landforms within the Waitemata Lowlands in the Auckland Region include low-lying alluvial terrain like much of Helensville in the west of Auckland, and the Manukau lowlands, floodplain features, lacustrine and coastal alluvium environments. Shallow meandering features including drainage gullies, streams, and river edges; and localised gullies with incised channels. The Waitemata

Lowlands also includes the relatively lower relief Waitemata Group terrain associated with the East Coast Bays Formation in the Auckland City urban areas.

The Waitemata Lowlands are characterised by localised slumping in the Alluvium, which is typically caused by rapid drawdown in the streambanks following flooding events and slumping caused by perching of groundwater in more permeable soils above lower permeability soil or weak rock. Instability on coastal cliffs of the East Coast Bays Formation includes localised rock fall as well as slope failures that are initiated by structural controls such as bedding and joints and the inclination of weathered soil and rock interfaces. Structurally controlled failures can be exacerbated by earthworks associated with development for infrastructure and subdivisions.

Figure 13: Examples showing the range of geomorphic settings within the Waitemata Lowlands

3.1.10.2 WAITEMATA HIGHLANDS

The Waitemata Highlands are in the hills to the north of Auckland City and are rolling to steep and dominated by the sandstones and mudstones of the Pakiri Formation.

The Waitemata Highlands are susceptible to shallow slumping and debris flows, and deeper defect-controlled failures. The defect-controlled failures include large block slides and wedge failures. During prolonged periods of rainfall, historic landslides can occasionally be reactivated, causing issues for roading networks and infrastructure. Typically, however, the most prevalent failures within the Waitemata Highlands are shallow soil/debris flows and slides rather than failures in the rock mass.

Slump failures and block slides can also occur that are structurally controlled by defects such as bedding dip and joints and the inclination of weathered soil and rock interfaces. Structural controls can also be exacerbated by earthworks associated with development for infrastructure, as well as subdivision development.

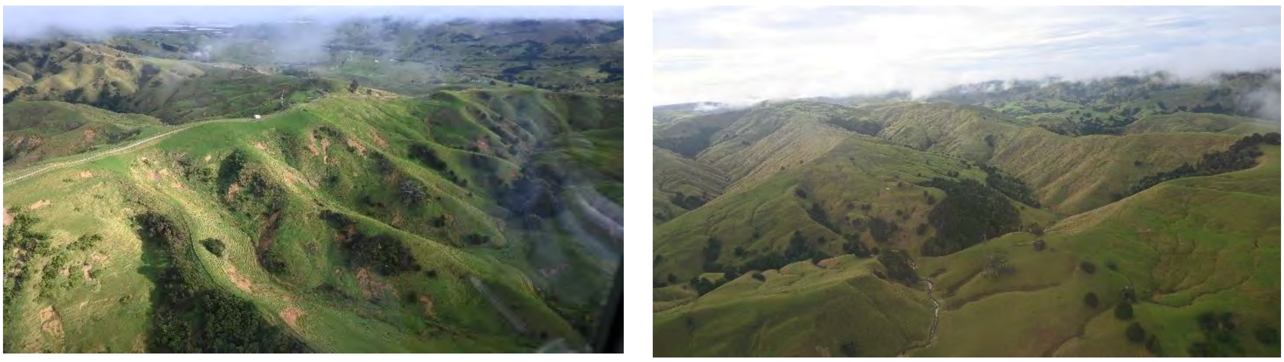

Figure 14: Examples showing the range of geomorphic settings within the Waitemata Highlands

3.2 CLIMATE

The climate of the Auckland Region is strongly influenced by the topography, most notably the Waitakere Ranges to the west and the coastal topography of the east and west.

Across the Auckland Region, higher terrain across the northern parts of the Waitemata Highlands, Waitemata Lowlands and Northland Allochthon are vulnerable to higher rainfall storm events.

Longer term weather patterns such as the El Niño and La Niña Southern Oscillation (ENSO) and Interdecadal weather cycles will influence the likelihood that the region suffers storm type events, including weather bombs and cyclones. These weather patterns may also help explain why the region suffers more in some years than in others. Expert advice from weather specialists such as NIWA can help in planning for an event of this type (Blair, 2007).

Temperature varies with elevation, with the lowest median annual average temperatures of the Auckland Region experienced at the highest elevations in the Hunua Ranges and Waitakere Ranges. Throughout the Auckland Region, annual temperatures are highest towards the east coast, around the Manukau Harbour and on the Hauraki Gulf Islands (Pearce, 2020; Paulik, et al., 2019).

Over the past 100 years, Auckland has seen an increase in temperature of about 1.6 degrees Celsius. The mean temperature of Auckland has increased over the 20th and early 21st century (Paulik, et al., 2019) and will continue to increase. By 2110, the mean annual temperature for the Auckland Region is projected to increase by 1.4 degrees Celsius. The whole of the Auckland Region is projected to warm, but the Waitakere Ranges is projected to experience less warming (Blair, 2007; Lorrey et al., 2017).

3.2.1 RECENT STORM EVENTS

3.2.1.1 AUCKLAND ANNIVERSARY STORM

The flooding caused by the Auckland Anniversary storm was unprecedented and exceeded previous flooding events in intensity and scale throughout Auckland's recorded history (Brooke, 2024).

Auckland experienced 160 mm of rain in six hours, totalling 245 mm of rainfall in 24 hours by Friday 27th of January 2023.

Infrastructure was impacted; more than 3,000 properties were without water supply, 26,000 properties without power. More than 39 roads fully closed on Sunday morning, due to extensive landslides throughout the region.

3.2.1.2 CYCLONE GABRIELLE

Cyclone Gabrielle which occurred between the 12th and the 14th of February 2023 caused extensive impacts for the Auckland Region and across the rest of Aotearoa's North Island Te-Ika-a-Māui. Rainfall amounts were recorded between 300-400 mm with the Auckland Region itself recording over 200 mm, the Waitakere area recording the most at 248 mm. As a result, over 140,000 landslides have been mapped across the affected areas. The landslides were mapped by GNS, NEMA, Manaaki Whenua, University of Canterbury, and the University of Auckland (Wilson, Broadbent, & Kerr, 2023; Brooke, 2024). Wind gusts during the event reached up to 130-140 km/h with Auckland Harbour Bridge recording a gust of 115 km/h.

Coastal areas were heavily impacted by waves up to 10 m high, with storm surges of over 0.5 m. Coastal inundation and flooding increased because of the storm surge.

4 LANDSLIDES IN THE REGION

4.1 INTRODUCTION

The commonly accepted definition of a landslide is "the movement of a mass of rock, debris or earth (soil) down a slope". This definition is used in AGS (2007a) guidance and in New Zealand guidelines for land use planning (de Vilder et al. 2024) in relation to landslide hazards.

Terms such as "landslip", "slippage" and "falling debris" are used to refer to landslide-type features in New Zealand regulations and codes like the Building Act 2004 and the Resource Management Act 1991. In this study, "landslide" is used generally to include all of these types of failures.

4.2 LANDSLIDE HAZARD ZONES

This section describes each of the different hazard zones within landslides, including the regression, failure, deposition, and runout zone, which each present different impacts. The characteristics of the landside zones and the consequent impacts are discussed below.

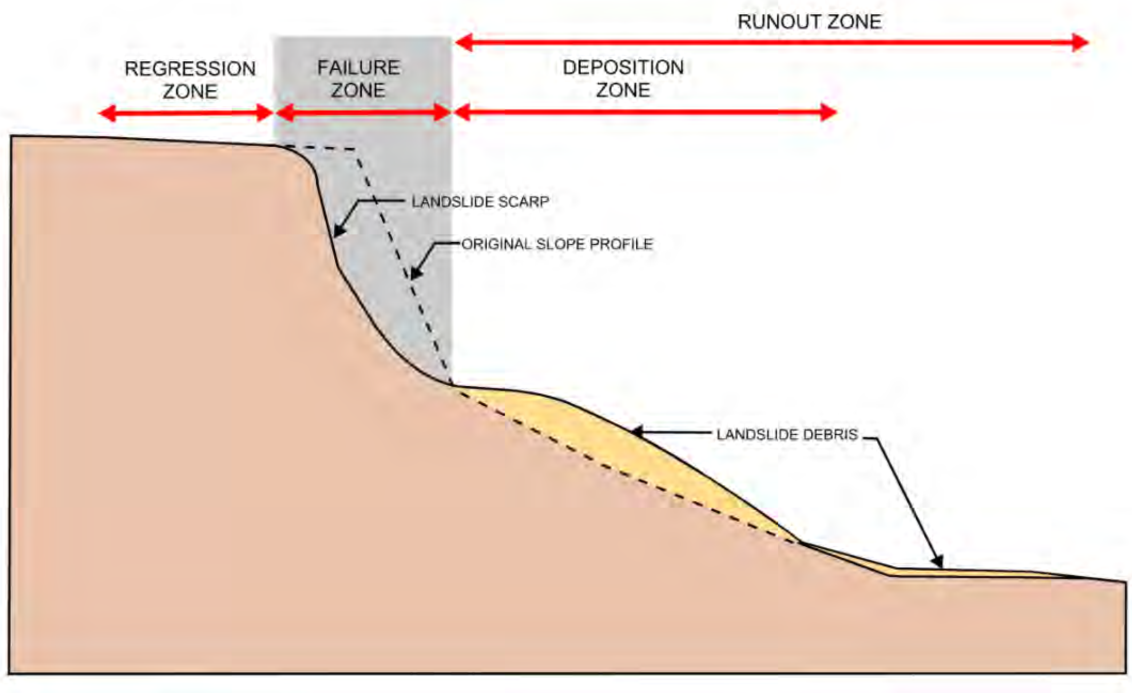

Figure 15: Landslide hazard zones.

Landslides in the Auckland Region are classified as shallow landslides or large-scale, slow-moving/relict landslides. The shallow landslide inventory in this study does not include potential areas of regression and only includes limited data on the extent of runout of the landslide debris. The large-scale landslide features within the inventory extend over most of or the full height of the local slope, observed in the aerial photography and maps as geomorphological features. These features therefore include accumulated slope deformation of both the failure source area and some of the depositional area.

Table 5: Landslide hazard zones

Landslide Zone	Definition
Failure Zone	Sloping ground that is vulnerable to failure, leading to landslides often in response to trigger events such as storms, sustained wet weather, erosion, earthquakes, human intervention etc.
Deposition Zone	The area at the lower part or bottom of the slope on which failed soil or rock debris accumulates.
Runout Zone	The materials mobilised in landslides can run out beyond the base of the slope, due to the inertia and velocity of the movement of debris, particularly when moving down from a larger height and / or in the presence of water which can facilitate movement over larger distances.
Regression Zone	After the initial landslides, there is often an over steepened head scarp which can lead to failure upslope of the original failure, encroaching into land which may not have been susceptible before the initial failure.

4.3 PREVIOUS STUDIES

Investigations of past landslides within the Auckland Region are summarised below:

- Kermode (1992) investigated as part of a Region wide study, concentrations of slope failure in weathered flysch seqeunces, and mapped as unstable ground.
- Williams (1996) carried out a slope instability hazard assessment for the Auckland Region. This assessment provided a general overview of slope instability in the Auckland Region at a scale of 1:250,000, including providing information on the risks and impacts of natural hazards. This assessment focused on geology, slope angle and height, soil weathering and previously known slope instability.
- Edbrooke et al. (2003) studied the geology and geological hazards in the Auckland Region, providing an overview of the engineering characteristics of the rock types, as well as variables influencing stability and commentary on potential causes of landslides.
- Amora (2015) carried out mapping and susceptibility assessment of deep-seated landsliding in the Southern Landslide Zone.
- Prebble and Williams (2016) addressed block slides on clay seams within the Auckland Region.

Several relict and active landslides have been mapped and presented in the geology maps for the region, such as the Kepa Road landslides (Figure 16). Landslides generally consist of unconsolidated to moderately consolidated deposits of largely coherent broken masses of rock, chaotic unsorted clay to boulder sized material. They are typically slow-moving landslides, usually 'large-scale' and with intermittent movements.

Figure 16: Large-scale landslide features at Kepa Road

4.4 LANDSLIDE MECHANISMS

The typical mechanisms by which slopes fail in the Auckland Region vary according to the lithology of the material and their degree of weathering or alteration. The stability of slopes is controlled by the strength of both the rock material and the rock mass, the degree of weathering, slope angle and groundwater conditions. Rock mass strength is dependent on the nature and attitude of fractures and bedding planes (discontinuities). Localised geological conditions and terrain as well as trigger events (e.g. storm events, earthquakes) generally determine which of these failure mechanisms occurs, while slope modification can also increase the likelihood of some failure mechanisms. Some landslides may exhibit characteristics of two or more failure mechanisms. Block diagrams of typical landslide types in the Auckland Region are shown in Figure 17.

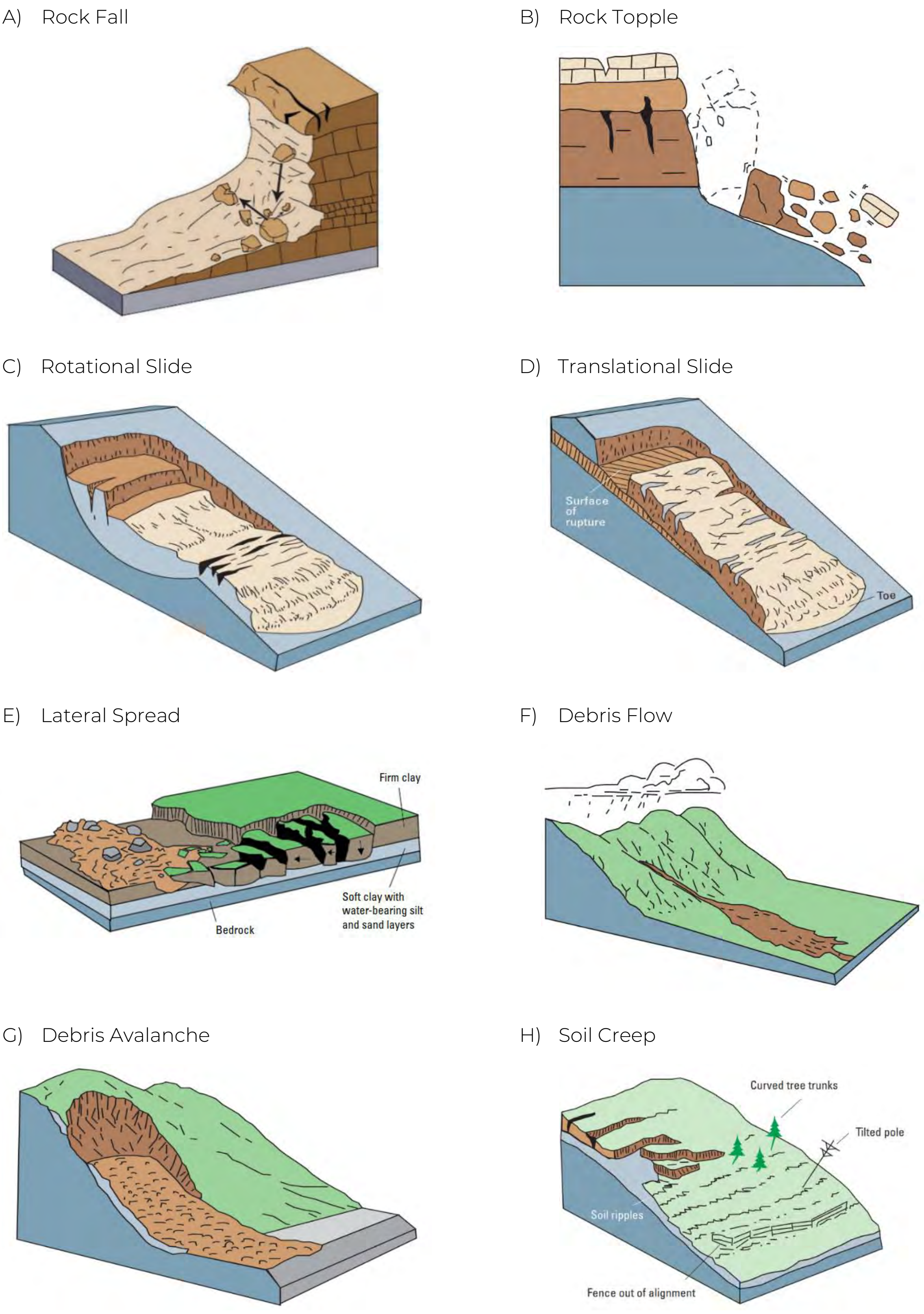

Figure 17: Schematic block diagrams of different landslide types, adapted from Highland & Bobrowsky (2008).

4.4.1 FLYSCH SEQUENCES

Weak mudstone rocks of late Tertiary age form an extensive carapace over the North Island of New Zealand. Bedding parallel clay seams and crush zones are common in interbedded mudstone rocks. The seams are 1-20 mm thick, and coatings are generally <1 mm thick. These clay seams have been identified as basal rupture surfaces to landslides around New Zealand.

Mapping throughout the Auckland Region has identified several areas with clay seams active as basal ruptures providing favourable conditions for large areas of instability. The Southern Landslide Zone is an area of ~100 km^2, where most of the landslides are mapped as deep-seated failures on bedding-parallel clay seam rupture surfaces (Amora, 2015).

Relatively steep cliffs around the Auckland coast typically expose gently dipping, but locally complexly deformed and or folded, well-bedded Waitemata Group sediments. In many areas these cliffs are receding rapidly (Moon & Healy, 1994; Moon & de Lange, 2010), particularly where the beds dip out towards the cliff (daylight), often with debris from slumps, rock falls, flows and slides littering the base.

4.4.2 ALLOCHTHONOUS ROCKS

Allochthonous rocks are present in the northern parts of the Auckland Region. These rocks are commonly unstable even on gentle slopes due to their sheared and fractured nature, their tendency to weather rapidly to weak, clay-rich materials, and groundwater pressures. Natural slope failures develop as an intermittent viscous fluid creep type failure, where toe bulging can occur downslope without any surface rupture (George & East, 2001).

Deep failures in Northland Allochthon sediments are controlled mainly by rock mass defects, but the more common shallow failures are controlled by the thickness of weathered material, its shear strength and water content, specifically its high piezometric head from hydrologically confined fractures (George & East, 2001).

4.4.3 VOLCANIC MATERIALS

Sensitive fine-grained pumice beds are present within Takaanini Formation (Tauranaga Group) alluvium in west Auckland at Te Atatu and Hobsonville, and in the East Tamaki–Manurewa area of east Auckland, and elsewhere. This material will flow if unconfined and saturated, especially if vibrated (Kermode, 1992).

Slope instability can occur where volcanic tuff and ash of the Auckland and South Auckland Volcanic Fields has been deposited on a steep Waitemata Group surface or on the moderate or steep sides of an explosion crater. Gradual downslope movement of the unconsolidated or weakly compacted volcanic materials can produce large landslide areas, such as those on the north side of the Orakei Basin explosion crater.

4.4.4 BASEMENT TERRAIN

Steep inland slopes formed on Waipapa basement are present near the eastern limit of the Auckland urban area, between East Tamaki and Clevedon. Weathered basement rocks form clay-rich soils that can fail as slumps, slides or flows on steep slopes; small shallow rotational slides and soil creep are particularly common. Downslope movement of weathered materials is often accelerated by water saturation following periods of rain.

5 LANDSLIDE INVENTORY

A regional landslide inventory was compiled as part of this study to assess the importance of landslide-influencing variables on landslide occurrence and to calibrate landslide susceptibility outputs.

The inventory was compiled from landslide mapping undertaken by WSP during this study and several existing data sources. An overview of the landslide inventory data compiled, the mapping undertaken, and the limitations of the inventory are provided below.

5.1 EXISTING DATA SOURCES

This study used several existing data sources on landslide occurrence in the Auckland Region (Table 6). Data ranged from large spatial databases of landslide features to written descriptions of individual landslides in site-specific geotechnical reports. Where available, spatial landslide data was compiled in ArcGIS Pro.

Table 6: Existing data sources compiled for the landslide inventories used in this study.

Dataset	Source	Number of landslides	Date range	Data type
GNS 1 : 250k Geological Map	GNS Science	6	Varies	Polygons of large-scale landslides
GNS 1 : 50k Pukekohe Geological Map	Bland et al. (2023)	757	Historical/relict landslides	Polygons of large-scale landslides
2023 Cyclone Gabrielle landslides	GNS Science, University of Canterbury	19,284 (Auckland Region)	August-October 2023	Point locations of shallow recent landslides
	GHD (2023)	231	2023	Polygons of shallow recent landslides
2017 Hunua Landslides	GNS Science (Lee, 2020)	6,168	March-April 2017	Points and polygons of source areas of shallow landslides
Southern Landslide Zone landslides	Amora (2015)	680	Historical landslides	Maps of large-scale landslides
2008 Auckland Landslides	Hancox & Nelis (2009)	2[1]	June-August 2008	Maps and aerial photographs of large-scale landslides

[1] Approximately 30 landslides were described by Hancox & Nelis (2009), but spatial data of the landslide locations and extents was not included. The 2 landslides referenced here were specific landslides used in the large-scale landslide susceptibility assessment.

5.2 LANDSLIDE MAPPING

Landslides in the Auckland Region have been considered in two distinct categories:

- Small-scale shallow landslides, and
- Large-scale landslide features.

This study mapped both categories of landslides identified in the Auckland Region. The different mapping approaches used for each landslide category are outlined in the following sections.

5.2.1 SHALLOW LANDSLIDES

Inventory mapping of shallow landslides was undertaken in 11 areas across the region (Figure 18) as part of this study. This mapping was carried out to supplement and fill gaps in the existing landslide datasets and to adequately represent the varied regional geology and terrain with landslide data for statistical analysis. Both landslide source and deposit areas were identified from aerial imagery and were captured as polygons in GIS at scales between ~1:500 and ~1:2,000. For the landslide susceptibility modelling, only source areas were used for raster analysis. Landslides were identified from the following sources:

- A 2023 Auckland imagery mosaic created from Maxar satellite data, supplied by Auckland Council was used as the primary layer for mapping landslides triggered by recent storms. Imagery was captured in March and April 2023 following the Auckland Anniversary Storm and Cyclone Gabrielle.
- Regional aerial imagery collected in 2010, 2017, 2020, and 2022 by LINZ was used to identify and map landslides that occurred before the Auckland Anniversary Storm and Cyclone Gabrielle in early 2023 (LINZ, 2013; LINZ, 2018; LINZ, 2022).
- Hillshade relief models derived from the regional 1 m LiDAR DEM were used to identify landslide scarps that are visible in the terrain but are vegetated and unable to be identified in aerial photography. The age of occurrence of these types of landslides are unable to be determined accurately. This mapping was used to supplement the landslide mapping in particular areas that were under-represented by landslides in the recent storm events such as the Auckland Volcanic Field and Southern Landslide Zone.

Attributes were assigned to each mapped landslide to capture additional information about the landslide and mapping process. For this study, the attribute schema developed for the New Zealand Landslides Database (NZLD) was used. This schema captures attributes such as landslide type, activity, cause, and movement type and is based off existing landslide description schemas (e.g. Cruden & Varnes, 1996; Hungr et al. 2014).

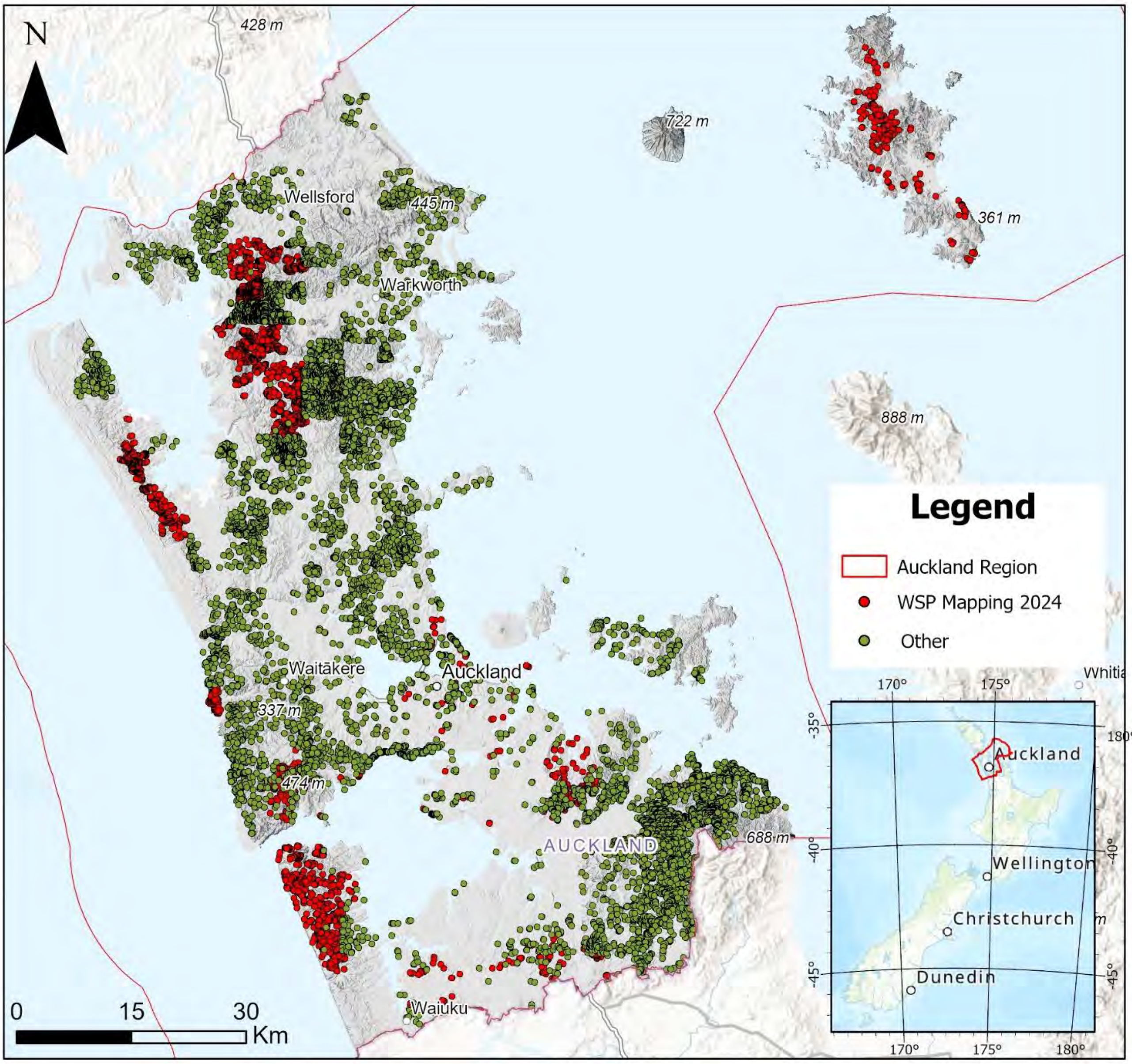

Figure 18: Map of the shallow landslide inventory.

5.2.2 LARGE-SCALE LANDSLIDE FEATURES

The desk study of landsliding characteristics across the region, as well as examination of digital elevation models (DEMs) from the LiDAR data in the initial stages of the study showed the presence of 'large-scale' landslide features across the region. These features are areas of hillslopes that show geomorphic evidence for slope deformation processes including downslope movement and incision or deflation. These typically extend over most of or the full height of the local hillslopes on which they are situated and also could laterally extend over 10s to 100s of metres. These were primarily identified using LiDAR-derived terrain models, supplemented by aerial photography and geomorphological maps. In comparison, the shallow landslides mapped by WSP were predominantly identified in the recent aerial imagery. The large-scale landslides have been mapped separately from the shallow landslides for consideration of large-scale landslide susceptibility across the region, as discussed in Section 2.2.

The mapping used LiDAR terrain data collected from 2016 to 2019 across the Auckland Region. Digital elevation models (DEMs) from the LiDAR data were processed into multi-directional hillshade, slope, and aspect rasters for use in the mapping. Recent 2023 satellite imagery from Maxar was also used. The mapping was done at approximate scales between 1:5,000 and 1:10,000.

Landslide features were identified based on geomorphological evidence such as: hummocky ground, slumped landslide body, ponding or other evidence for shallow groundwater tables, steepened head scarp area (relative to the surrounding slope), eroded toe area, and evidence for past slope movement such as changes in slope angle, lateral scarps, or uphill-facing scarps (Figure 19). The types of features identified in this mapping ranged from single discrete landslides, with well-defined lateral and head scarps delineating the area of slope movement (Figure 20a) to broad areas of accumulated or distributed deformation that may consist of multiple areas of slope movement (Figure 20b).

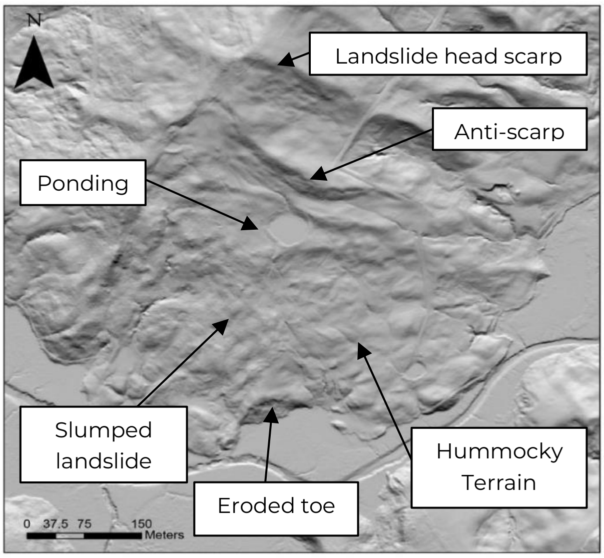

Figure 19: Example of large-scale landslide mapped in Northland Allochthon.

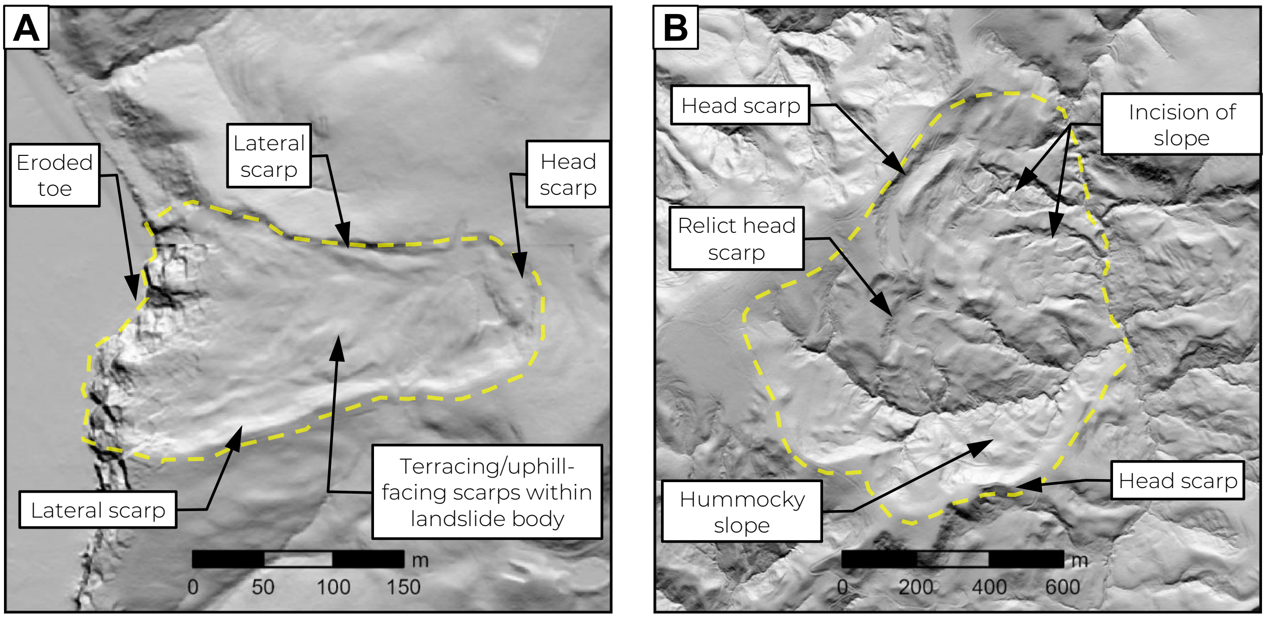

Figure 20: Examples of different large-scale landslide characteristics. (A) Single discrete landslide, Okahukura Peninsula. (B) Large-scale area of accumulated slope movement and distributed deformation, near Helensville.

The mapped landslide features are generally considered to be predominantly inactive or relict, however, it is acknowledged that the exceptional rainfall of early 2023 did result in measurable movement on some of these landslides. The exact age, level of activity, failure mechanisms, type and rate of deformation, and the potential triggers for the landslide features were not investigated as part of this study. Given the predominantly rounded geomorphic expression, these features may have developed over a period of time in the recent geological past (i.e., on a time scale of tens or hundreds to thousands of years), and the mapped areas may therefore represent accumulated slope deformation rather than a single discrete failure. The focus was to map as much of the Auckland Region as possible, to capture the different geomorphic sub-regions and identify areas of land that showed geomorphic expression of landslide processes on a significantly larger scale than the recent shallow landslides, so that the susceptibility variables for these large-scale features could be analysed separately.

5.3 LANDSLIDE INVENTORIES

5.3.1 SHALLOW LANDSLIDES

The shallow landslide inventory is summarised in Table 7 and shown in Figure 18. This includes the available landslides collated from the NZ Landslides Database, recent landslides mapped by GNS Science, University of Canterbury and GHD following the 2023 storms, and landslides mapped by GNS following a significant storm event in 2016, as well as the landslides mapped by WSP as part of this study.

Table 7: Number of shallow landslides in each sub-region in the inventory used for this study.

Sub-Region	Number of shallow landslides[1]	Area (km^2)	Landslide density (N/km^2)
Active Dunes	446	282	1.58
Auckland Volcanic Field (AVF)	186	137	1.36
Awhitu	2,275	272	8.36
Hauraki Islands	224	317	0.71
Northland Allochthon	1,277	419	3.05
South Auckland Volcanic Field (South AVF)	135	189	0.72
Southern Landslide Zone (SLZ)	412	55	7.46
Waipapa / Hunua	7,102	589	12.06
Waitakere	944	232	4.07
Waitemata Highlands	10,693	1,490	7.17
Waitemata Lowlands	1,468	942	1.56

[1] Includes all landslides from pre-existing datasets and landslides mapped by WSP for this study

5.3.2 LARGE-SCALE LANDSLIDE FEATURES

The large-scale landslide inventory is summarised in Table 8. This includes landslides mapped by GNS Science for the Auckland Region (1:250,000) (GNS Science, 2020) and the South Auckland area (1:50,000) (Bland et al. 2023), and an un-published MSc thesis (Amora, 2015). In the GNS 1:50,000 landslide dataset, GNS have categorised the landslides into 'landslide terrain', 'landslide terrain inferred', and 'landslide vacated'. These features were then combined into single polygons in GIS. Amora (2015) mapped landslide features according to Cruden and Varnes (1996), by the presence of arcuate features, sharp breaks in slope, and presence of hummocky ground. The range of sizes (plan areas) of the large-scale landslide features in the landslide inventory are shown in Figure 21, and the distribution of the locations of the landslides are shown in Figure 22.

Table 8: Number of large-scale landslides in each sub-region in the inventory used for this study.

Sub-Region	Number of Large-Scale Landslides	Area (km^2)	Landslide density (N/km^2)
Active Dunes	8	250	0.03
Auckland Volcanic Field (AVF)	15	170	0.09
Awhitu	65	341	0.19
Hauraki Islands	5	320	0.02
Northland Allochthon	121	458	0.26
South Auckland Volcanic Field (South AVF)	320	157	2.04
Southern Landslide Zone (SLZ)	682	51	13.34
Waipapa/Hunua	451	621	0.73
Waitakere	41	232	0.18
Waitemata Lowlands	223	924	0.24
Waitemata Highlands	709	1365	0.52

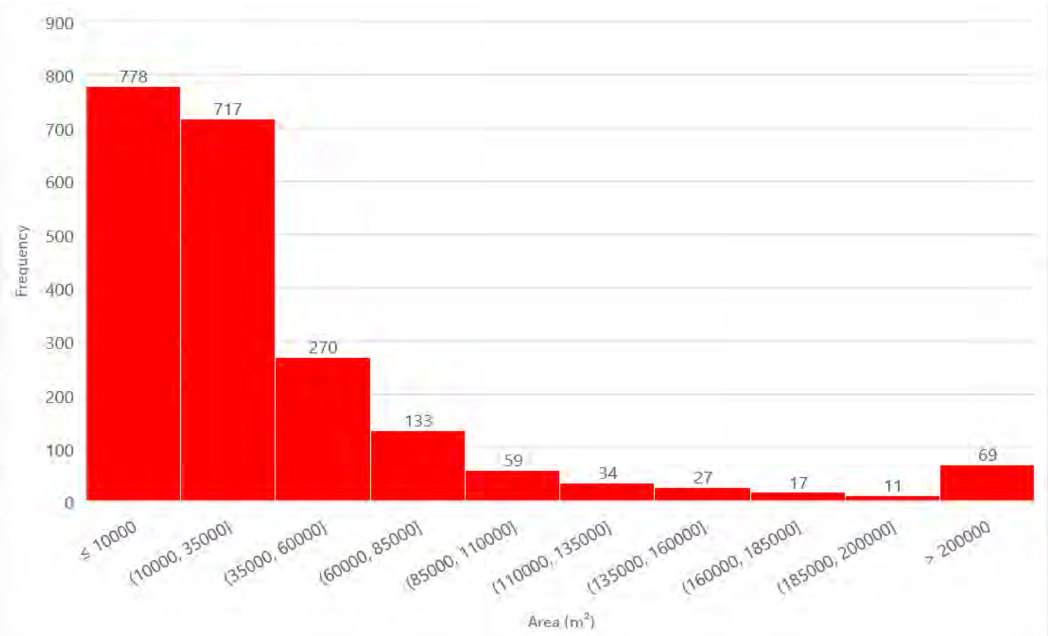

Figure 21: Distribution of landslide sizes (area) of large-scale landslides in the inventory

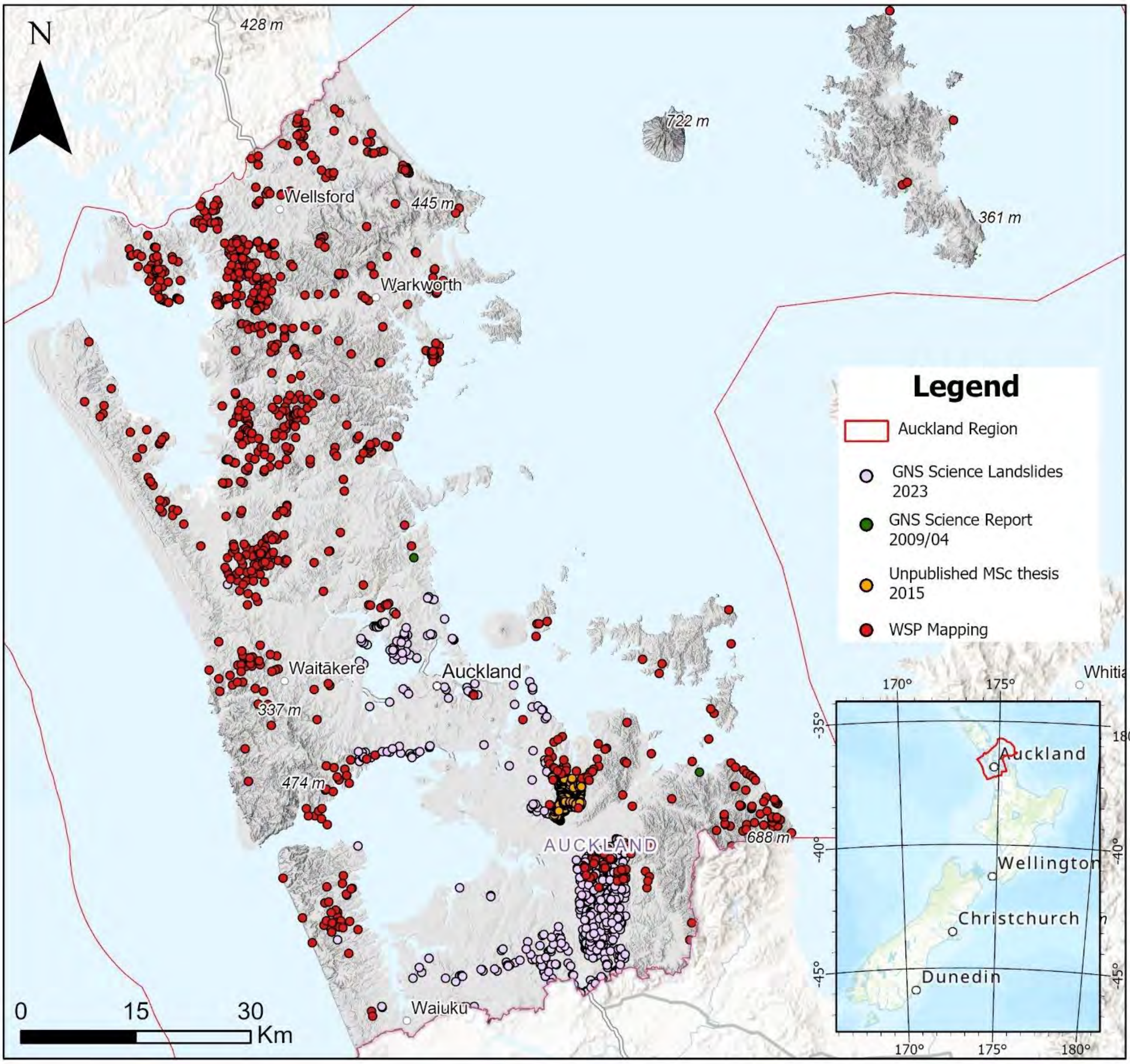

Figure 22: Map of the large-scale landslide inventory.

5.4 LIMITATIONS

Limitations associated with the landslide inventory compiled for use in the susceptibility assessment are discussed below.

5.4.1 LOCATIONAL INACCURACIES

Locational accuracy of the landslide data in the inventory is variable and sometimes poor. For the scarp line data and landslides mapped by WSP from historic imagery, locational accuracy is dependent on the quality of aerial imagery used to identify the features. For example, cloud cover in the aerial imagery increased the difficulty of identifying landslides.

Large-scale landslides were mapped by WSP based on observations of landslide features (e.g. hummocks, head scarps) in the terrain. This is dependent on the quality of aerial and LiDAR imagery as well as being subjective to the mapper.

5.4.2 DIFFERING DATA TYPES

Landslides are mapped as different data types (points, lines and polygons). This means there is inconsistency in the format of the landslide inventory. It is also difficult to use scarp line data for correlation with landslide-influencing factors, as the landslide extent downslope can be unclear.

5.4.3 BIAS TOWARDS PARTICULAR TRIGGERING EVENTS

The susceptibility map is intended to be independent from specific storm event scenarios, however the available inventory data is often dominated by features triggered in specific events. The shallow landslide inventory compiled to date is dominated by landslides triggered in the 2023 Auckland Anniversary and Cyclone Gabrielle storms, and the 2017 'Tasman Tempest' storm largely due to the timing of these events with respect to this study.

6 SHALLOW LANDSLIDE SUSCEPTIBILITY

6.1 OVERVIEW

The assessment of shallow landslide susceptibility for this study focused on the slope failure zone (refer Section 4.2). Assessment of landslide runout or head scarp regression was not included in this study.

Landslide susceptibility was evaluated from a dataset of variables compiled on a grid of 32 m x 32 m cells in ArcGIS Pro. The dataset was split into the 11 geomorphic sub-regions used in this study (refer Section 3). Each sub-region was analysed independently using logistic regression, a commonly used method to evaluate landslide susceptibility (Lombardo & Mai, 2018) in the statistical software environment R. The model outputs for each sub-region were divided into five classes to define zones of Very Low, Low, Moderate, High and Very High landslide susceptibility. The classified susceptibility maps for the sub-regions were merged in GIS to create a single map of shallow landslide susceptibility for the whole region.

This section presents an overview of the developed methodology, mapping outputs, potential limitations, and opportunities for further development.

6.2 DATASET PREPARATION

A series of commonly used landslide susceptibility variables were considered for the shallow landslide susceptibility analysis (Table 3). These input data variables were resampled to a 32 m-resolution grid in ArcGIS Pro, and exported to text files for analysis within R.

Prior to logistic regression modelling, continuous variables (e.g., slope angle and local slope relief) were rescaled and standardised in R. Standardisation brings features with different units and ranges of values to a common scale, allowing direct comparison of the variables' importance in influencing landslide susceptibility. These variables where standardised as follows:

$$z = \frac{x - \mu}{\sigma} \qquad \text{(Eq. 1)}$$

Where:

- z = standardised value of the variable
- x = original value
- μ = mean of all values in the dataset
- σ = standard deviation of all values in the dataset

Categorical variables (e.g., Geomorphon landform and geological unit) were transformed to dummy variables by creating k-1 binary response variables for each factor variable with k levels.

The details for the original input datasets, and data preparation and transformation processes applied to each variable, are discussed below.

6.2.1 GEOMORPHOLOGY

The 'Geomorphology' input data category consists of slope angle, local slope relief, slope profile curvature, aspect and landform (Geomorphon). The details of the source datasets and processing methods used for the Geomorphology variables are summarised in Table 9.

Table 9: Data processing for geomorphology variables

Variable	Data source / derivation	Data type	Original resolution	Geoprocessing (ArcGIS)	Transformation (R)
Slope angle	Derived from LiDAR DEM[1]	Raster	1 m	Slope (Surface Parameters tool)	Standardised
Local slope relief	Derived from LiDAR DEM[1]	Raster	4 m	Focal Statistics to calculate the minimum value in window of 6x6 cells, subtracted from the elevation of the grid cell.	Standardised
Aspect	Derived from LiDAR DEM[1]	Raster	1 m	Aspect (Surface Parameters tool)	Standardised
Slope profile curvature	Derived from LiDAR DEM[1]	Raster	1 m	Curvature (Surface Parameters tool)	Standardised
Landform	Derived from LiDAR DEM[1]	Raster	32 m	Geomorphon landforms tool	Factor data type and dummy variable transformation

[1] Merged Auckland North LiDAR 1 m DEM (2016-2018) and Auckland South LiDAR 1 m DEM (2016-2017)

6.2.2 GEOLOGY

Geological units from the 1:250,000 GNS QMAP were combined into 14 groups based on geological formations as described in Section 3 and summarised in Table 10.

Table 10: Geology units used for shallow landslides.

Variable	Data source / derivation	Data type	Original resolution	Geoprocessing (ArcGIS)	Transformation (R)
Geological unit	GNS QMAP	Polygon	1:250,000	Polygon to raster, resampled and snapped to 32 m grid	Factor data type and dummy variable transformation
Categories:	Volcanic-CVZ; Greywacke; Cemented Dune Sands; Takaanini Formation; QMAP-Landslides; Auckland Volcanic Field (AVF)-Lava; AVF-Scoria; AVF-Tuff; Northland Allocthon; Waitemata; Waitemata-SLZ; Waitakere-VC; Fill; Te Kuiti Group				

6.2.3 *HYDROLOGY*

The hydrological variables used were Distance to Stream and Distance to Overland Flow Path. The data sources and processing methods used to derive these variables are summarised in Table 11. Both variables were treated as factors, and transformed into dummy variables in R.

Table 11: Data processing for hydrology variables

Variable	Data source / derivation	Data type	Original resolution	Geoprocessing (ArcGIS)	Transformation (R)
Distance to stream	LINZ NZ river centrelines LINZ NZ river polygons	Polyline Polygon	1:50,000 1:50,000	Buffer of 0.01 m applied to the centreline polylines to convert to polygons, and merge with river polygons. Multiple-Ring Buffer tool to generate buffers of 5 m, 10 m, and 20 m. A buffer of >20 m was generated with Erase tool using the Auckland Region boundary. Polygon outputs converted to a raster with a cell size of 32 m.	Factor data type and dummy variable transformation
Distance to overland flow path	Auckland Council Open Data	Polyline	-	Multiple-Ring Buffer tool to generate buffers of 5 m and 10 m. A buffer of >10 m was created using the Erase tool with the Auckland Region boundary. Polygon outputs converted to a raster with a cell size of 32 m.	Factor data type and dummy variable transformation

6.2.4 LAND COVER

The land cover variable was derived from the 1:50,000 LRIS Land Cover Data Base (LCDB) v5.0. The categories were reclassified in ArcGIS, as listed in Table 12. The corresponding categories were treated as factors in R and transformed into dummy variables.

Table 12: Landcover reclassification for LCDB v5.0 categories

Landcover Database v5 Category	Reclassified Category	Grouping
Built-up Area (settlement)	Artificial areas	2
Transport Infrastructure		
Sand or Gravel	Bare	5
Surface Mine or Dump		
Gravel or Rock		
Broadleaved Indigenous Hardwoods	Forest	1
Deciduous Hardwoods		
Exotic Forest		
Forest - Harvested		
Indigenous Forest		
Manuka and/or Kanuka		
High Producing Exotic Grassland	Grassland	4
Low Producing Grassland		
Urban Parkland/Open Space		
Landslide	Landslide	6
Gorse and/or Broom	Scrub/shrubland	3
Mixed Exotic Shrubland		
Orchard, Vineyard or Other Perennial Crop		
Short-rotation Cropland		
Flaxland		
Matagouri or Grey Scrub		
Fernland		
Estuarine Open Water	Water bodies	7
Herbaceous Freshwater Vegetation		
Herbaceous Saline Vegetation		
Lake or Pond		
Mangrove		
River		

6.2.5 LANDSLIDES

A dataset of landslides was compiled for this study as discussed in Section 5. In ArcGIS, landslide source points were converted to polygons using a nominal buffer of 5 m, combined with landslide source areas that were mapped as polygons, and then all landslide polygons were converted to a raster with 32 m resolution. Grid cells that contained a landslide were assigned a value of 1; cells without a landslide were assigned a value of 0. In R, the landslide data was treated as a categorical factor with possible values of 0 or 1, and therefore dummy transformation was not required. The total number of cells with and without landslides for each geomorphic zone is shown in Table 13.

Table 13: Number of cells with and without landslides for each geomorphic zone for shallow landslides

Geomorphic Zone	Number of cells with landslides	Number of landslides	Number of cells without landslides
Active Dune	1,030	446	291,270
Auckland Volcanic Field	238	186	141,823
Awhitu	4,132	2,275	277,359
Hauraki Islands	875	224	347,094
Highlands Waitemata	16,689	10,705	1,487,429
Hunua Ranges[1]	12,483	7,102	772,335
Lowlands	1,751	1,491	991,607
Northland Allochthon	1,776	1,277	417,838
South Auckland Volcanic Field	475	292	222,868
Southern Landslide Zone	584	412	35,508
Waitakere Ranges	1,827	944	227,378

[1] The input datasets for the Hunua Ranges sub-region extended beyond the Auckland Region boundary, to encompass the physiographic extent of the Hunua Ranges and include all available landslide data, maximising the training data for the logistic regression model.

6.3 ANALYSIS

A grouped LASSO penalised logistic regression model and a standard logistic regression model were fit to the input data using R Statistical Software to calculate landslide susceptibility (Yang & Zou, 2014). Logistic regression is a statistical model that predicts the probability of an event occurring given a set of predictor variables. The LASSO penalty is an extension of this model, that prevents overfitting and improves generalisation (Meier, van de Geer, & Buhlmann, 2008). The grouping of predictor variables is undertaken to encourage comparisons by predictor variable rather than within predictor groups. This is done to identify the most important variables influencing landslide susceptibility and shrinking or removing less relevant variables. A subsequent logistic regression model was fit excluding the unimportant predictors as identified by the LASSO penalisation. Variable importance is described in the following section.

The outputs from the model are predicted probabilities of landslide occurrence for each cell in the data. In terms of landslide susceptibility, probabilities can be interpreted as the likelihood of that area to generate a landslide given the site conditions, which is dependent on the occurrence of a triggering event (e.g., a storm).

Validation of model performance has been undertaken using analysis of ROC curves and accuracy model metrics to confirm that meaningful geological interpretations can be made from the model outputs. The coefficients removed in each iteration from LASSO penalisation are analysed to assess variable importance.

6.3.1 MODEL THEORY

To undertake landslide susceptibility analysis, grouped LASSO penalised logistic regression and standard logistic regression modelling was used. The model was coded as 0 for absent landslides, and 1 for a landslide occurrence. The probability of landslides given the site conditions is defined as:

$$P(Y = 1|x_i) = \frac{\exp(\beta_0 + \beta_1 x_{i1} + \cdots \beta_k x_{ik})}{1 + \exp(\beta_0 + \beta_1 x_{i1} + \cdots \beta_k x_{ik})} \quad \text{(Eq. 2)}$$

Where:

- Y: the binary response (No Landslide/Landslide)
- $x_{i1\ldots}x_{ik}$: vector of predictor variables
- $\beta_0 \ldots \beta_k$: coefficients estimated by the model

The logistic group LASSO estimator $\widehat{\beta_\lambda}$ is given by the minimiser of the convex function (Meier, van de Geer, & Buhlmann, 2008):

$$S_\lambda(\beta) = \sum_{g=1}^{G} s\,(df_g)\left\|\beta_g\right\|_2$$

The tuning parameter $\lambda \geq 0$ controls the amount of penalisation and was chosen through 10-fold cross validation.

6.3.2 IMPLEMENTATION

Implementation of the LASSO logistic regression method to the landslide dataset is similar to the method outlined in Lombardo & Mai (2018). All instances of the minority class (i.e., landslide presence = 1) were selected and combined with an equal number of randomly selected majority class instances (landslide absence = 0) to create a balanced dataset. This balanced dataset was split, with 75% of the data used for model training and the remaining 25% reserved for testing. Within the testing data, a portion of the majority class instances were replaced with an additional, randomly ordered majority class dataset. This was done to ensure that over the course of the iterations, all the majority classes will be tested at least once.

A grouping vector was assigned in accordance with variables and their dummy encodings. A 10-fold cross validation of the training dataset was performed to estimate λ. The value of λ was chosen that gave the minimum mean cross-validated error on the training dataset. A grouped LASSO logistic regression model was fitted using the estimated λ, then applied to the testing dataset. Variables identified as unimportant by LASSO penalisation were discarded, and a subsequent standard logistic regression model was fit. The coefficients generated from the logistic regression model, the predictions generated, and the testing data used were stored for later analysis. This process was repeated 5,000 times for each sub region. The susceptibility for each cell was calculated using the mean prediction for each cell from the 5,000 model iterations.

6.3.3 *MODEL PERFORMANCE*

ROC CURVES

The predictive power of each iteration was analysed to confirm that meaningful geological interpretations can be made. This was done through analysis of Receiver Operating Characteristics (ROC) curves and the area under the ROC curve (AUC).

A ROC curve is used to assess the overall diagnostic performance of a test. In the context of landslide susceptibility, it informs how well the model is able to distinguish between landslide occurrences and absences. The y axis of a ROC curve plot represents the True Positive Rate, which is the proportion of correctly identified landslide occurrence by the model. The x axis represents the False Positive Rate, which is the proportion of correctly identified landslide absences by the model. The ROC curve represents the trade-off between the two metrics at different classification thresholds. The area under the ROC curve (AUC) is used to determine the overall performance of the model. An AUC value of 1 is a perfect classifier, whilst an AUC value of 0.5 indicates that model has no ability to distinguish between classes. The mean AUC values from the final, averaged dataset are displayed in Table 14, with ROC curve plots by iteration in Figure 23.

Table 14: AUC values by sub-region

Sub-region	Map AUC
Active Dune	0.92
Auckland Volcanic Field	0.85
Awhitu	0.82
Hauraki Islands	0.77
Highlands Waitemata	0.80
Hunua Ranges	0.73
Lowlands	0.87
Northland Allochthon	0.79
South Auckland Volcanic Field	0.86
Southern Landslide Zone	0.76
Waitakere Ranges	0.73

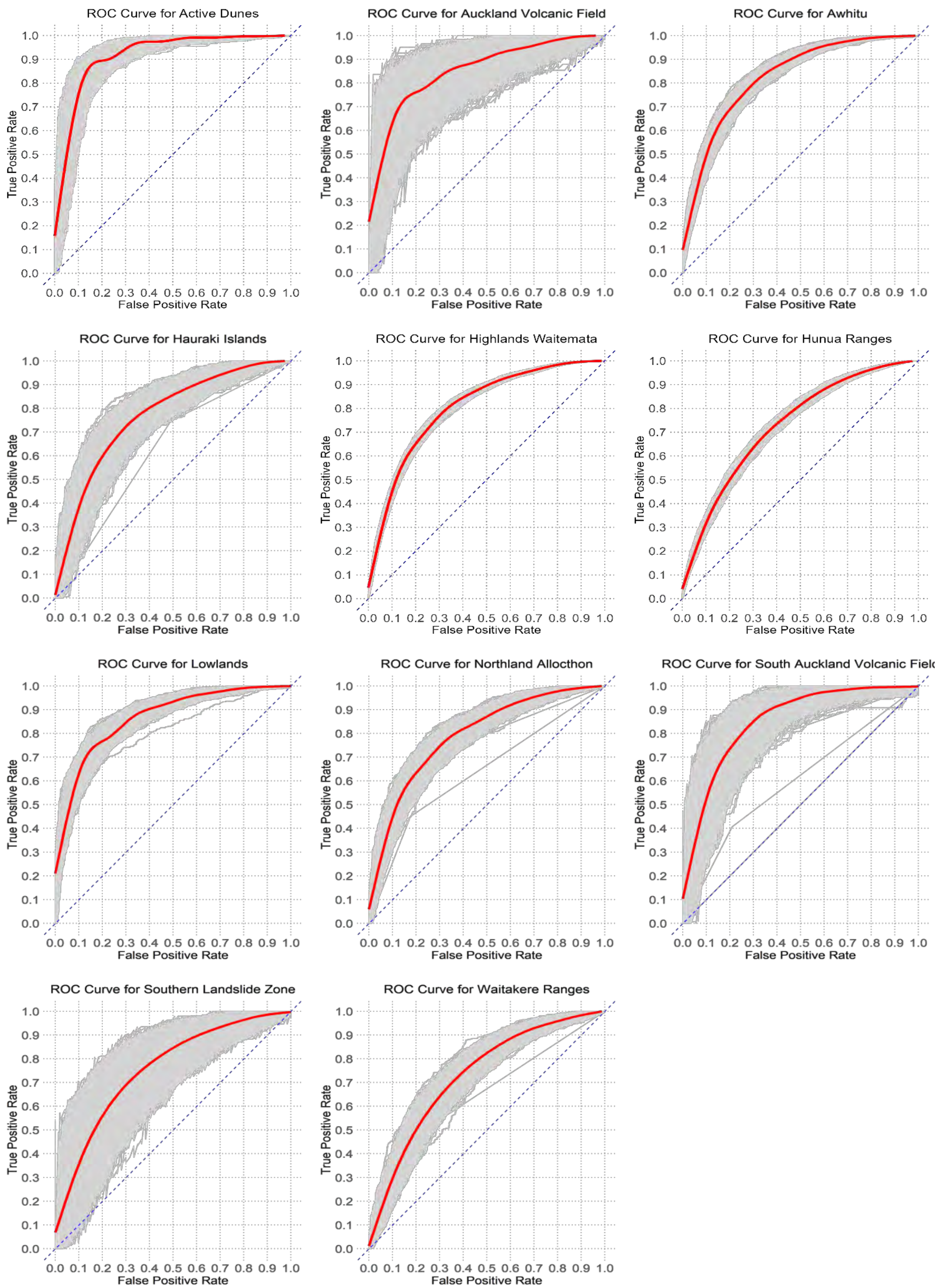

Figure 23: ROC curves for sub-regions. Gray lines show the ROC curve for each iteration, with the mean curve displayed in red. The blue dashed line is included for comparison and represents a ROC curve with an AUC value of 0.5.

VARIABLE IMPORTANCE

The final susceptibility map is built using the mean prediction for each cell over the 5,000 iterations rather than defining an average logistic regression equation (Eq. 2). However, the process of LASSO penalised logistic regression initial modelling fitting is informative of variable importance for landslide susceptibility. For each of the 5,000 iterations per sub region, a LASSO penalised logistic regression model was fitted. The logistic regression model will fit an equation using the input data to predict landslide occurrence. Predictor variables with a higher effect on the landslide occurrence will be assigned larger values, indicating a significant increase or decrease in the probability for this predictor value. In the process of LASSO penalisation, the number of predictor variables are reduced to only those most important to predicting the binary outcome (Landslide Occurrence), with unimportant variables shrunken to zero. Inclusion of a variable from the LASSO penalisation indicates that variable has a significant impact on the landslide susceptibility calculated in a given iteration, and is therefore dependent on the training data used in that iteration.

For each sub-region, variable 'importance' has been calculated (Table 15), defined as the proportion of time the predictor value was not excluded during LASSO penalisation. The importance value is descriptive of variable reliability, and a higher value represents that in most iterations, this predictor value was important in calculating landslide susceptibility.

Table 15: Variable importance for geomorphic sub-regions

Geomorphic Sub-region	Variable importance								
	Slope Angle	Local Slope Relief	Slope Profile Curvature	Aspect	Geomorphon	Geology	Distance to stream	Distance to overland flow path	Land cover
Active Dunes	1.00	1.00	0.99	0.60	0.47	1.00	0.26	0.57	0.91
Auckland Volcanic Field	1.00	1.00	0.98	0.99	1.00	0.1-1.00	1.00	0.97	1.00
Awhitu	1.00	1.00	0.95	1.00	1.00	0.07-0.36	0.99	0.52	0.83-1.00
Hauraki Islands	1.00	1.00	1.00	0.84	0.80-0.98	0.98-0.99	0.07	0.86	0.01-0.49
Waitemata Highlands	1.00	1.00	1.00	1.00	1.00	0.01-1.00	1.00	1.00	1.00
Waipapa / Hunua	1.00	1.00	1.00	1.00	1.00	0.91-1.00	1.00	0.61	1.00
Waitemata Lowlands	1.00	1.00	0.98	0.99	1.00	0.1-1.00	1.00	0.97	1.00
Northland Allocthon	1.00	1.00	0.99	0.76	0.98	0.06-0.41	0.95	0.97	0.98-1.00
South Auckland Volcanic Field	1.00	1.00	1.00	0.54	0.4	0.79-1.00	0.91	0.78	0.81-1.00
Southern Landslide Zone	1.00	1.00	0.99	1.00	1.00	0.13-1.00	1.00	1.00	1.00
Waitakere Ranges	1.00	1.00	1.00	1.00	0.64-0.99	0.01-0.05	0.12	0.64	0.49-0.56

Due to grouped LASSO penalisation being used, the majority of categorical variables have the same importance for each zone. Large ranges in the variable importance in Table 15 are likely due to some dummy categorical variables being absent from the training data for some model iterations (and consequently being excluded during penalisation). For example, dummy variables for distance to overland flow path would be absent if none of the randomly selected cells in a given iteration were within 10 m of an overland flow path.

VARIABLE CORRELATION

The correlations between variables used in the analysis were assessed for each sub-region to ensure representative model weighting of the variables. Correlations between continuous variables were assessed using the Pearson Correlation Coefficient, and correlations between categorical variables were assessed with Cramers V effect size measure for Chi-Square tests. No extreme values indicating strong correlations were identified and all variables were included in the model for each sub-region. The detailed results are provided in Appendix C.

UNBALANCED DATASET ANALYSIS

Because the landslide raster layer consists of significantly more 0's than 1's, logistic regression analysis was also carried out on the full (i.e. unbalanced) datasets to cross-check the results from the balanced LASSO models. This involved fitting a grouped LASSO penalised logistic regression model to the entire data set and discarding variables identified as unimportant by LASSO. Once a reduced dataset was created, a standard logistic regression model was fitted using 500 bootstraps, with the model coefficients stored. The coefficients from the 500 bootstraps were averaged, then applied to the dataset using equation 2 to calculate the susceptibility.

Performance of the unbalanced bootstrap model was evaluated in terms of AUC and was plotted. AUC values for the unbalanced model were very similar to the balanced model, typically differing between +/- 0.01-0.04 AUC points (Figure 24). The raw model outputs showed some differences between the models when plotted, however once susceptibility classes were calculated, the maps were very similar. Both balanced and unbalanced models were able to identify the key patterns influencing landslide susceptibility in the Auckland region. The balanced model was selected to use for the final output as it was more computationally efficient, and more iterations could be run, increasing confidence in the results.

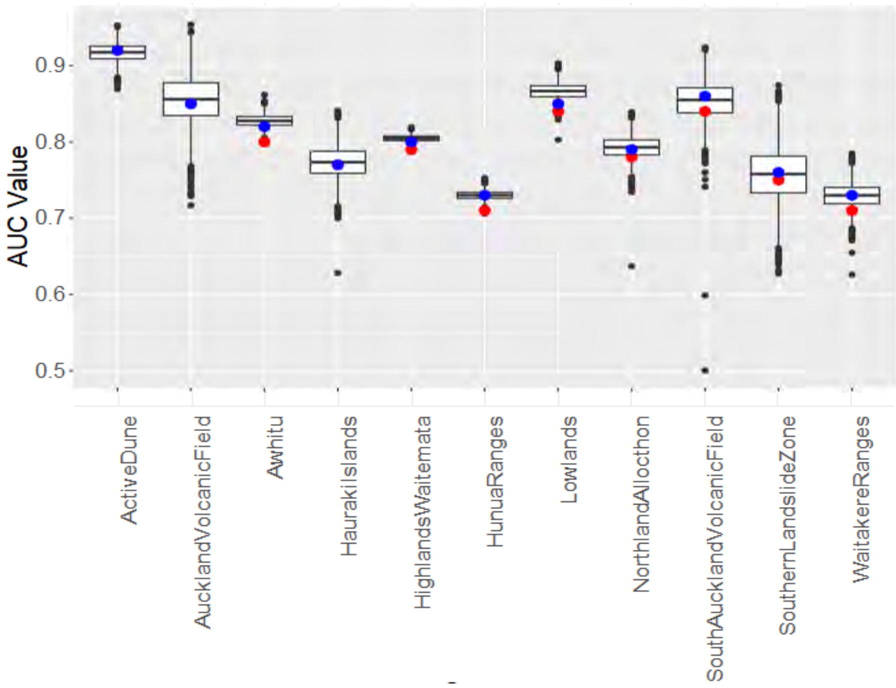

Figure 24: Logistic regression model performance from models trained within each sub-region. Model performance is measured by area under the ROC curve (AUC).

Each box plot shows the results of 5,000 model iterations using balanced datasets. Blue dots indicate the map AUC for the balanced datasets; red dots indicate the map AUC for unbalanced datasets modelled using 500 bootstrap iterations.

6.4 SHALLOW LANDSLIDE SUSCEPTIBILITY CLASSIFICATION

Classification of the model outputs is necessary so the degree of susceptibility can be displayed spatially with common descriptors that enable the susceptibility of different areas to be compared, rather than numerical values that may represent different susceptibilities in different areas. Use of descriptors with a uniform meaning enables wide use of the maps (e.g., by planners, geotechnical professionals, members of the public etc.).

International best practice guidance for landslide susceptibility zoning typically use descriptors of Very Low, Low, Moderate and High (AGS, 2007a; Fell, et al., 2008), but there is no single, standardised methodology for determining the class boundaries, as regional landslide susceptibility may be assessed using knowledge-driven (heuristic) methods or data-driven (statistical) methods, and the resulting susceptibility will be expressed in qualitative or quantitative form depending on the method used (Corominas, et al., 2014). The general objective is to include the greatest number of landslides or proportion of landslide-prone land in the higher susceptibility classes whilst trying to minimise the area for those classes (Fell, et al., 2008).

Three approaches were tested to develop the landslide susceptibility classes. These are described below. Appendix C provides more detailed outputs from the logistic regression models for comparing these classification methods.

METHOD 1 – AGS (2007) QUANTILES

For this method, four classes were chosen to represent landslide susceptibility (very low to high), consistent with AGS (2007a) and Fell et al. (2008). The mean prediction of landslide probability for each grid cell was used as the basis for classifying landslide susceptibility, and each of the sub-regions was classified separately. Threshold values of landslide probability for each susceptibility class were selected for each sub-region to align with the recommended proportions of landslide-prone land and landslide area provided in Table 4 of AGS (2007a). These were validated by comparison with the distribution of probabilities for landslide cells within each sub-region dataset.

METHOD 2 – EQUALLY-SPACED LOG BINS

Initially, four classes (from Very Low to High) were used to represent landslide susceptibility, following AGS recommendations. After review of the initial maps and discussion with Auckland Council, it was agreed to present the maps using five susceptibility classes (Very Low, Low, Moderate, High and Very High).

For this method, log transformations were taken of the predicted probabilities from the logistic regression models. A cut-off quantile of the resulting log-distribution was chosen to represent the boundary between very low and low susceptibility; the 75th percentile log-prediction was used as the cut-off for initial testing. The log-transformed probabilities were split into evenly spaced bins above this cut-off to define the boundaries for the low to very high classes.

This method reduced the amount of land within the higher susceptibility classes (relative to method 1), except for the Auckland Volcanic Field, Lowlands and South Auckland Volcanic Field sub-regions, where the proportions of land in the moderate and high/very high classes were higher. Changing the threshold percentile for the boundary between the very low and low classes was not found to improve the overall classification of the region satisfactorily, and consequently this method was not used for classifying the model outputs for the final susceptibility map.

METHOD 3 – ACCURACY CUT-OFF

For this method, the mean predicted probability from the logistic regression models were used to identify the highest accuracy cut-off value for predicting whether a landslide exists within a grid cell (i.e., where values above the cut-off correctly predict a landslide, and values below the cut-off correctly predict no landslide). These cut-off values are used to define the boundary between 'susceptible' and 'not-susceptible' classes; this is taken as the boundary between the low and moderate susceptibility classes for all sub-regions other than the Lowlands, Auckland Volcanic Field and South Auckland Volcanic Field. Jenks natural breaks are used to divide the predictions below the cut-off value into very low and low susceptibility, and above the cut-off value into the moderate, high and very high susceptibility classes. For the Lowlands, Auckland Volcanic Field and South Auckland Volcanic Field sub-regions the cut-off is taken as the boundary between very low and low susceptibility as this was found to better represent the level of susceptibility based on review of the geomorphic characteristics and mapped geology in those sub-regions. Jenks natural breaks are used to divide the predictions above the cut-off into the low to very high classes. The cut-off values, model accuracies, and susceptibility class boundary values for each sub-region are listed in Table 16.

Table 16: Shallow landslide susceptibility classification using method 3 (accuracy cut-off)

Sub-region	Highest accuracy cut-off		Susceptibility class boundaries (mean predicted probability)				
	Prediction value	Accuracy	Very low	Low	Moderate	High	Very high
Active Dunes	0.48	85.2%	≤ 0.18	≤ 0.48	≤ 0.63	≤ 0.81	≤ 1
Awhitu	0.47	75.1%	≤ 0.24	≤ 0.47	≤ 0.61	≤ 0.76	≤ 1
Auckland Volcanic Field	0.51	78.2%	≤ 0.51	≤ 0.61	≤ 0.73	≤ 0.86	≤ 1
Hauraki Islands	0.52	71.3%	≤ 0.23	≤ 0.52	≤ 0.63	≤ 0.77	≤ 1
Highlands	0.49	73.5%	≤ 0.23	≤ 0.49	≤ 0.60	≤ 0.75	≤ 1
Hunua Ranges	0.51	66.9%	≤ 0.22	≤ 0.51	≤ 0.61	≤ 0.72	≤ 1
Lowlands	0.51	78.6%	≤ 0.51	≤ 0.61	≤ 0.72	≤ 0.85	≤ 1
Northland Allochthon	0.50	72.4%	≤ 0.28	≤ 0.50	≤ 0.62	≤ 0.76	≤ 1
South Auckland Volcanic Field	0.43	78.3%	≤ 0.29	≤ 0.52	≤ 0.60	≤ 0.70	≤ 1
Southern Landslide Zone	0.52	76.3%	≤ 0.43	≤ 0.52	≤ 0.68	≤ 0.82	≤ 1
Waitakere Ranges	0.48	67.4%	≤ 0.30	≤ 0.48	≤ 0.58	≤ 0.70	≤ 1

Following testing, review and discussion of the outputs of the three classification methods with Auckland Council, Method 3 was used to classify the results from the logistic regression into susceptibility classes. The classified sub-region datasets were then merged to create the overall regional susceptibility map, an overview of which is shown in Figure 25, with larger scale maps provided in Appendix A.

The proportions of land area and landslide population within each of the susceptibility classes across the region are summarised in Table 17. The characteristics of slopes within the susceptibility classes are discussed below.

Table 17: Shallow landslide susceptibility classification summary

Susceptibility class	Study area		Slope unit landslide inventory			
	Area in class (km^2)	Proportion of total area of region	Area of landslides in class (km^2)	Proportion of total area of landslides	Proportion of total area of class	Proportion of total area of region
Very Low	2,308	47%	6	2%	0.3%	0.1%
Low	1,451	29%	24	6%	1.7%	0.5%
Moderate	478	10%	53	14%	11.2%	1.1%
High	400	8%	97	26%	24.1%	2.0%
Very High	288	6%	195	52%	67.6%	4.0%

Given the region-wide nature of this study, analysis of site-specific conditions and stability are not captured in the susceptibility mapping.

VERY HIGH AND HIGH SUSCEPTIBILITY

Zones of high to very high susceptibility consist primarily of steep to very steep hillslopes, coastal cliffs and bluffs, and moderate to steep slopes underlain by weak or soft materials. These areas have a high concentration of past slope instability.

MODERATE SUSCEPTIBILITY

Zones of moderate susceptibility consist of moderately steep to steep slopes, such as rounded or undulating hills and land on the margins of gullies or at the base of hillslopes. Areas of flatter land that are near steep slopes such as the edges of terraces or the peaks of hills and ranges, as well as areas of shallower slopes underlain by weaker materials, also fall within this zone.

The potential for landslides in these areas will depend on site-specific conditions such as the thickness and strength of surficial soils, the underlying geological formations, and the prevailing drainage and groundwater conditions, as well as the intensity and duration of the triggering event.

LOW AND VERY LOW SUSCEPTIBILITY

Zones of low susceptibility comprise the shallowest slopes at the margins of hillslopes and gullies, as well as areas with low to moderate slopes in more competent geological materials. Zones of very low susceptibility are comprised of flat areas of the alluvial and volcanic terrains (away from terrace edges and gullies), valley floors, and coastal flats.

Given the region-wide appraisal undertaken in this study, land classed as having a low or very low landslide susceptibility cannot be confirmed to have no potential for land instability. Site-specific conditions that locally increase landslide susceptibility may not have been captured at the scale of mapping appropriate for this regional study, particularly where the terrain has been anthropogenically modified. In addition, these areas could be subject to runout of debris or debris flows from adjacent slopes or gullies.

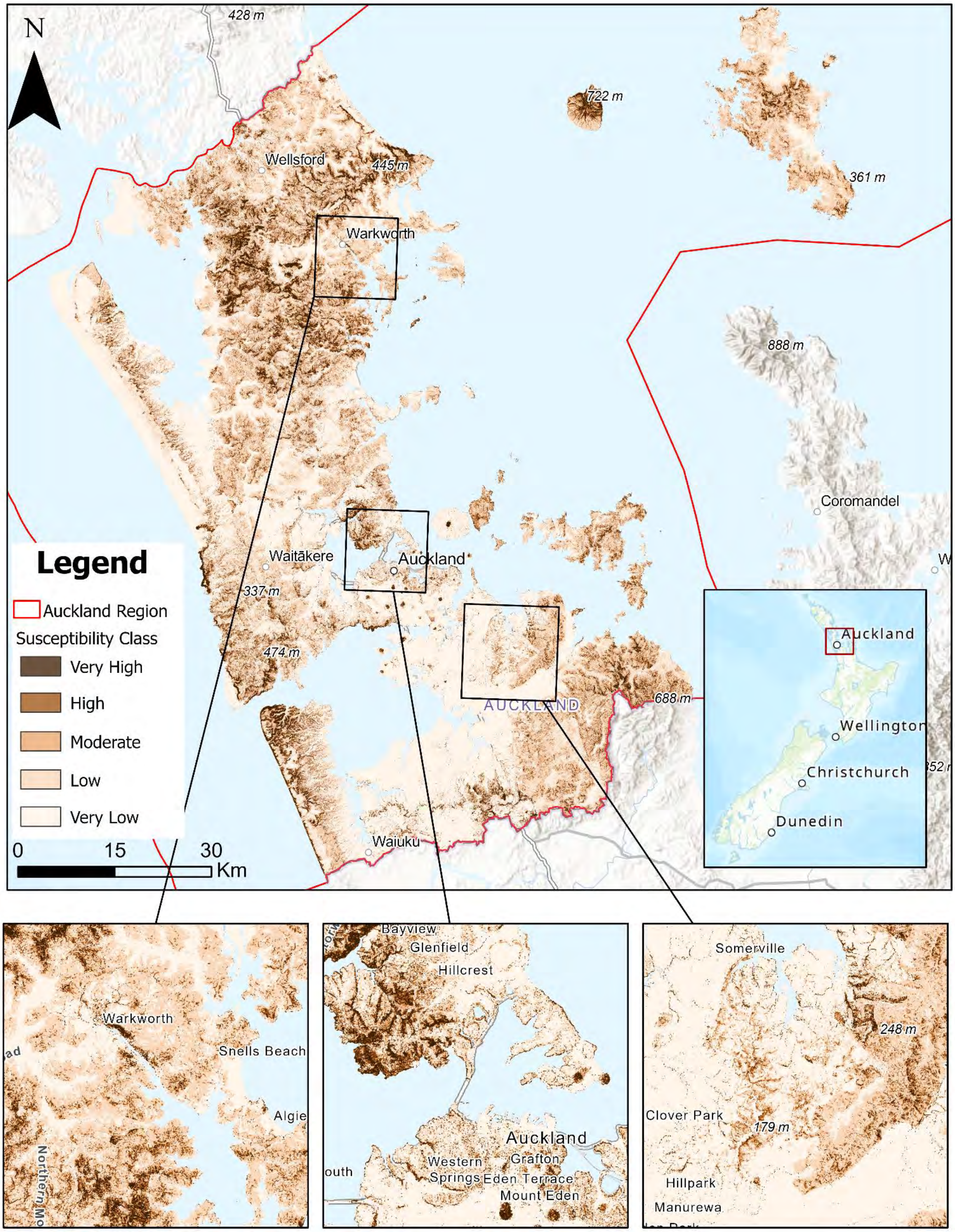

Figure 25: Shallow susceptibility map with inset maps showing Warkworth, Auckland central, and Manurewa areas

6.5 LIMITATIONS AND UNCERTAINTIES

SCALE OF ASSESSMENT

The landslide susceptibility mapping completed in this study represents a desk-based, region-wide assessment that was carried out from examination of remotely sensed data including LiDAR and aerial imagery, along with regional-scale datasets. The susceptibility analysis was undertaken on a 32 m resolution grid, but will not fully capture small or low height slopes.

No access was gained to properties, and site-specific stability assessments have not been undertaken. Property owners and developers should seek independent advice from a suitably qualified Geotechnical Professional (PEngGeol and/or CPEng) with appropriate relevant experience, on land stability at their particular property when considering development or the existing level of slope instability hazard.

RESOLUTION OF INPUT DATASETS

The study utilised a variety of geospatial data, including LiDAR-derived DEM data, regional geological mapping, and digitised polygon, point and line features. As these data have been collected and/or digitised at different resolutions, artefacts in the landslide susceptibility classes can potentially be created where individual input layers do not align correctly. For example, the geological units were mapped at a small scale (1:250,000), and consequently some of the boundaries of the units do not align with the higher resolution LiDAR-derived slope layers, resulting in inaccuracies in the assessment in those boundary areas.

LANDSLIDE INVENTORY

The performance of a logistic regression model is dictated by the quality and representativeness of the input data. As landslide susceptibility analysis targets areas affected by landslides that occurred in the past, input variables reflecting long-term characteristics are required. The shallow small-scale landslide inventory collated for this study only spans the last ~10 years and is particularly dominated by landslides triggered in the large storm events in 2023, and the locations of landslides are dependent on the rainfall distribution in those events. The landslide inventory is based on the best information available, and includes new mapping specifically carried out to target parts of the region with the fewer landslides in the inventory. However, given the large area and varied geology of the Auckland Region, the inventory compiled to date is likely to under-represent the long-term landslide characteristics of parts of the region. This is particularly applicable for shallow landslides as these will be obscured by vegetation regrowth relatively quickly after they occur and are therefore harder to identify in inventory mapping using aerial photographs. As shown in Figure 23 and Figure 24, areas with fewer landslides (refer Table 13) show significantly more variability in AUC and accuracy values over the 5,000 iterations, showing that a lack of landslide data will limit the predictive capability of the logistic regression model.

Additionally, the majority of the landslides in the inventory are those triggered by the 2023 storms, which were mapped by GNS Science and University of Canterbury researchers as part of a North Island-wide landslide mapping project following Cyclone Gabrielle. Because of the large area affected and very high number of landslides triggered by those events, the landslides in the inventory are represented by points at the approximate centre of the landslide failure source areas. For this study, grid cells with 32 m resolution spacing were constructed for logistic regression analysis. Using input point feature data, any landslides that are larger than the 32 m cells will not be accurately represented in the model, as only the cell containing the centre of the landslide will be classified as a landslide and the surrounding cells would be incorrectly classified as 'No Landslide'.

LANDSLIDE TRIGGERS

The scope of this study is to prepare a landslide susceptibility map for land use planning purposes. Landslide susceptibility mapping does not quantify the number of small landslides which may occur within a given time period (or the annual probability of large landslide occurrence), as these are covered by hazard mapping (Fell, et al., 2008). The triggers for landsliding can include climatic, seismic, hydrological, and anthropogenic factors such as rainfall, earthquakes, groundwater changes, slope modification, etc. Data for these triggering factors have very important temporal components and are necessary for the conversion of landslide susceptibility maps to hazard maps (Corominas, et al., 2014), but not necessarily for susceptibility mapping itself. The frequency and intensity of trigger events such as rainfall is also changing due to climate change.

The landslide inventory used for this study spans multiple years and many triggering events, and the specific date of occurrence for each landslide has not been recorded or cannot be determined from the available data. As a result, the intensities of triggering factors that caused the landslides (such as rainfall depth and soil moisture conditions) cannot be established. Datasets for landslide triggers have therefore not been included in the susceptibility analysis, and the use of the landslide susceptibility map as a basis for forecasting the location of landsliding for particular scenarios (e.g. forecast storm events) is limited. Further investigation and documentation of the triggers of landslides within the landslide inventory would be necessary for quantified estimation of the distribution of potential landslides for forecast rainfall events.

CLIMATE CHANGE

The susceptibility maps have been trained on data of past landslides that have occurred in the various sub-regions. These past landslides occurred given the rainfall and other trigger events in the past. Given the intensity and frequency of severe weather events is considered likely to be increasing over time due to climate change, the susceptibility maps map not accurately predict the degree of susceptibility to future landslides.

DIFFERENTIATION OF LANDSLIDE TYPE AND RUNOUT

The desk study highlighted the key failure mechanisms in the various geological formations across the region, and we note that different mechanisms have different failure and runout characteristics. As there is limited identification of the failure mechanisms available in the landslide inventory, it is not currently possible to differentiate the failure types in the susceptibility maps presented in this study. Similarly, the susceptibility considers only the vulnerability of the hillslope surface to failure, and does not take into account the potential for regression into flatter land above over time following the initial failure, or the areas below that may be affected where the landslide debris is deposited or runs out onto flatter land.

MODIFICATION OF SLOPES

There are many anthropogenically modified slopes in the region, including cuttings, fills, in-ground soakage features and retaining structures built during residential and commercial development, as part of road and rail networks, and for quarries or landfills etc. Slope modification often exacerbates existing slope stability issues and makes a landslide more likely during a subsequent storm or earthquake, but it is also possible for slope modification to trigger landslides in the absence of rainfall or an earthquake. Slope modification could also enhance stability, for example if it involves drainage, soil reinforcement, anchoring, retention, or other similar modification.

The available information used for the landslide susceptibility analysis does not differentiate engineered or modified slopes from unsupported natural slopes, and the regional scale of the study makes it impractical to identify those slopes and assess whether individual slopes have been engineered and the standards to which they have been designed. Mapping the location and extent of modified slopes as a direct input for the analysis is beyond the scope of this study, and information relating to the design of retaining walls, cuts, fills, soak holes etc., which would be important for assessing the potential for failure, is typically not available.

Given that anthropogenic slope modification features are not considered in the susceptibility analysis, actual landslide susceptibilities may differ from those presented in this study and the susceptibility mapping may overestimate or underestimate the true failure susceptibility. Confirmation of susceptibilities within individual properties would require more detailed, site-specific information on the subsurface conditions and the efficacy of any existing measures to mitigate instability hazards, which is beyond the scope of this study. It should also be noted that engineered slopes may not have been designed for large earthquakes, severe storms or the effects of climate change.

DATA CURRENCY

The capture of landslide susceptibility is determined by the scale, quality and age of the input datasets, and the scale of the assessment. Any modifications to the datasets that post-date the versions used here (e.g., more recent acquisition of LiDAR) will not be reflected in the susceptibility maps. Actual susceptibilities may therefore differ from those presented in this study and are subject to change with time.

The maps of landslide susceptibility presented in this study should not be regarded as static. The use of updated and/or higher quality datasets and, in particular, improved mapping of past and existing landslides can allow the susceptibility zones to be refined. We recommend that the landslide susceptibility mapping be updated using new data periodically, or when there is significant step change in data available or need.

6.6 FUTURE UPDATES

The mapped landslide susceptibility zones are able to be updated as the input datasets are refined or new datasets become available. We recommend that the availability and coverage of input data (e.g., LiDAR terrain data, geology mapping, landslide inventory mapping, groundwater or soil moisture models) is reviewed periodically and updated when there is a step change in data available or need. Future updates to the maps could include:

- More detailed analysis and mapping using a higher resolution raster cell size (smaller cell size).
- Extend the susceptibility assessment to include landslide runout and regression.
- Capture landslide susceptibility for priority areas at a larger scale than this regional study, where better data is available.
- Refinement of the geomomorphic sub-regions using higher resolution geological mapping and improved regional landslide mapping.
- Revision of landslide variables and weightings with future contributions to regional landslide mapping and published studies.
- Review and update the maps when more landslide data becomes available, particularly with new data that represents ongoing climate change.

7 'LARGE-SCALE' LANDSLIDE FEATURES

7.1 OVERVIEW

A study of the geomorphology and previous studies of landslides in the region indicated the presence and significance of large-scale landslides across the region. Examination into shaded relief (hillshade), slope, and aspect rasters derived from the 1 m LiDAR DEM, as well as the 2023 satellite imagery from Maxar, showed the presence of 'large-scale' geomorphic features that extend over most of or the full height of the hillslope. Large-scale landslide features could also laterally extend over 10s of metres, and can be seen in the aerial photography and maps as geomorphological features. The larger-scale landslides also represent a significant landslide hazard in the region and hence are important for land use planning and consideration of the resilience of lifelines. Therefore, the mapping of these large-scale landslides as a separate map was discussed with the Council and was included as part of the scope of the landslide susceptibility study. This section presents an overview of the methodology developed for mapping of the large-scale landslide susceptibility, the mapping outputs, potential limitations, and opportunities for further development.

7.2 ASSESSMENT APPROACH

Large-scale landslide susceptibility has been assessed for the Auckland Region through an analysis of the additional inventory of large-scale landslides compiled specifically as part of this study. The landslides mapped have been analysed by considering factors (refer to Table 3) that have an influence on the susceptibility of slopes to large-scale landslides in each geomorphic sub-region. A weighting has been assigned to each factor based on its judged relative importance to landslide susceptibility. An explanation of each factor in regard to the large-scale landslide susceptibility assessment and its weighting is outlined in the following sections.

For the large-scale susceptibility assessment, the Auckland Region was divided into Slope Units (SU) which are small hydrogeological regions bounded by drainage and divide lines (such as ridges and valleys) (Alvioli, et al., 2016). A SU represents a single slope, a combination of adjacent slopes, or a small catchment. Slope units were generated in ArcGIS Pro using the ArcHydro extension and the 1 m DEM supplied by Auckland Council. Each slope unit was then assessed in terms of its susceptibility to large-scale landslides through inventory analysis, literature review, field work, and professional judgement. The results are summarised in Section 0.

7.3 LANDSLIDE SUSCEPTIBILITY FACTORS

7.3.1 LANDSLIDE TERRAIN SUB-REGIONS

Previous investigations have highlighted geomorphological areas such as Northland Allochthon (George & East, 2001; Winkler, 2003) and the Southern Landslide Zone (Amora, 2015) to be susceptible to large-scale landslides.

In the landslide inventory compiled for this study, the Southern Landslide Zone (SLZ), South Auckland Volcanic Field, and the Waipapa / Hunua geomorphic sub-regions have the highest landslide density (landslides / km^2) whereas the Auckland Volcanic Field (AVF), Hauraki Islands, and Active Dunes have the lowest landslide density (Table 18). The landslide terrain sub-regions with the highest landslide densities are those where existing landslide inventories have been used (e.g. Amora, 2015; Bland et al., 2023) and could be over-represented compared to other sub-regions.

The mapped geology units were not taken directly as an input factor layer in the large-scale landslide susceptibility analysis. Instead, the geology and geomorphology were grouped into sub-regions and landslide susceptibility factors were determined for each landslide terrain sub-region using a combination of inventory analysis, literature review, field work, and professional judgement. This includes consideration of the typical geological materials (and their strength characteristics) and previous knowledge of large-scale instability within the sub-regions. The Northland Allochthon, Southern Landslide Zone, and Waitemata Highlands sub-regions are assessed as having the highest susceptibility to large-scale landslides while the Hauraki Islands, Waitakere Ranges and Auckland Volcanic Field are assessed to be less susceptible. The susceptibility factors shown in Table 18 reflect the relative susceptibility of each sub-region to large scale landslides. For example, the volcanic sub-regions such as Waitakare Ranges, Auckland Volcanic Field, South Auckland Volcanic Field and Hauraki Islands have lower (<0.4) susceptibility factors, where Southern Landslide Zone, Waitemata Highlands and Northland Allochthon have the highest susceptibility factors (1).

Table 18: Large-scale landslide density per geomorphic sub-region, with susceptibility factor values.

Sub-region	Landslides (N)	Area (km^2)	Landslide density (N/km^2)	Susceptibility factor
Active Dunes	8	250	0.03	0.5
Auckland Volcanic Field (AVF)	15	170	0.09	0.1
Awhitu	65	341	0.19	0.6
Hauraki Islands	5	320	0.02	0.2
Northland Allochthon	121	458	0.26	1
South Auckland Volcanic Field (South AVF)	320	157	2.04	0.4
Southern Landslide Zone (SLZ)	682	51	13.34	1
Waipapa / Hunua	451	621	0.73	0.7
Waitakere	41	232	0.18	0.2
Waitemata Lowlands	223	924	0.24	0.4
Waitemata Highlands	709	1365	0.52	1

7.3.2 STRUCTURE

Geological structure can also influence large-scale landslide susceptibility (Varnes, 1978) due to the orientation of layers, bedding or other defects with respect to the surrounding terrain. Meentemeyer & Moody (2000) classified slopes as either cataclinal, anaclinal, or orthoclinal based on the conformity of slope angle, slope aspect, and bedding dip (Figure 26). Cataclinal slopes are classified where the difference between bedding dip direction $(\boldsymbol{\alpha})$ and Aspect of slope $(\boldsymbol{A})$ is 0°± 45°. Anaclinal slopes occur if the difference between $\boldsymbol{\alpha}$ and $\boldsymbol{A}$ is 180°± 45°, and orthoclinal slopes occur if the difference is 90 °± 45° or 270° ± 45°. We have adopted these slope classifications for geological structure in this study.

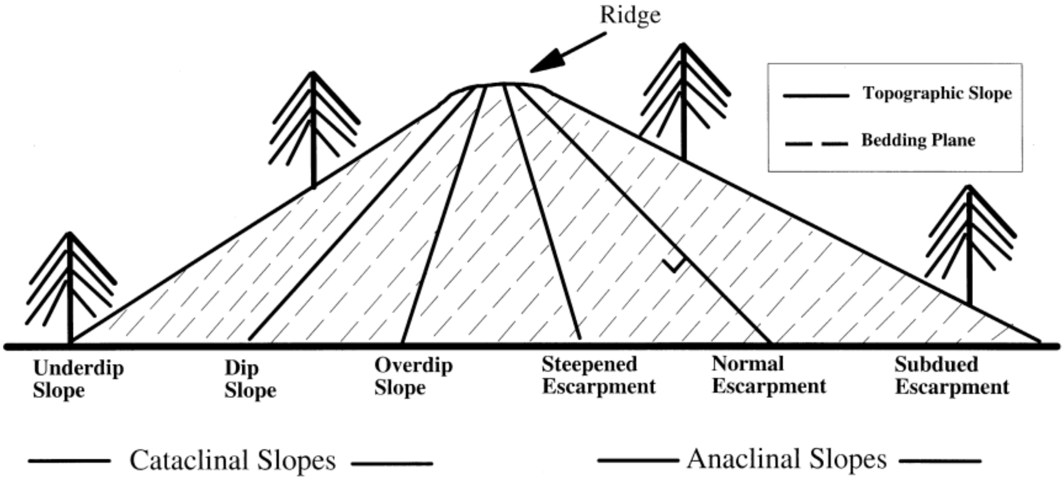

Figure 26: Classification of alignment between topography and bedding planes (Meentemeyer & Moody, 2000). Orthoclinal orientations not shown.

To identify the bedding dip and dip direction of slopes, structural measurements from GNS have been used and were filtered based on any persistent bedding and discontinuities (GNS Science, 2020). Polygons were then drawn in GIS around measurements with similar dip and dip directions. Within each polygon, the mean strike and dip value were calculated. A 200 m buffer was drawn around singular or isolated structural measurements and assigned the corresponding dip and dip direction value. The 200 m buffer was selected as it corresponded to the scale of the mapped structural measurements. At this scale, it provided a suitable radius to capture singular or isolated structural points. Where a SU overlapped a grouped structural polygon, it was assigned the corresponding structural value of that polygon. All remaining SU that overlapped a singular buffer polygon was assigned the corresponding value of the buffer.

To determine whether slopes were cataclinal, anaclinal, or orthoclinal the chord length subtended by the angle between bedding dip direction $(\boldsymbol{\alpha})$ and slope direction $(\boldsymbol{A})$ has been computed on the unit circle. Where the chord length $(\boldsymbol{L})$ describes a continuous function between 0 and 2 of the unit circle by the following equation:

$$\boldsymbol{L} = \sqrt{(\cos\boldsymbol{\alpha} - \cos\boldsymbol{A})^2 + (\sin\boldsymbol{\alpha} - \sin\boldsymbol{A})^2}$$

Where $\boldsymbol{\alpha}$= Bedding dip direction, and A = Slope Direction

If $0 \le L \le 0.7654$, then <u>Cataclinal slope</u> (0°±45°)

If $0.7654 < L \le 1.8478$, then <u>Orthoclinal slope</u> (90 °±45° or 270° ±45)

If $1.8478 < L \le 2$, then <u>Anaclinal Slope</u> (180°±45°)

Cataclinal and Anaclinal slopes can also be further partitioned based on the conformity between dip angle $(\boldsymbol{\theta})$ and slope angle $(\boldsymbol{S})$.

For Cataclinal Slopes

If $-5° \leq \theta - S \leq 5°$ then = Dip Slope

If $\theta - S > 5°$, then = Underdip Slope

If $\theta - S < 5°$, then = Overdip Slope

For Anaclinal Slopes

If $-5° \leq \theta - S \leq 5°$ then= Normal Escarpment

If $\theta - S > 5°$, then = Subdued Escarpment

If $\theta - S < 5°$, then = Over steepened Escarpment

Where $\boldsymbol{\theta}$= Bedding Dip, and S= Slope inclination

Cataclinal slopes have unfavourable bedding orientation with respect to slope, and they are assessed as the most susceptible while anaclinal and orthoclinal are assessed as less susceptible (Table 19). In this study due to lack of structural data, and highly variable geology, slopes were not further partitioned from cataclinal, anaclinal and orthoclinal slopes.

In cases where SU lacked structure data, these SU initially could only receive a maximum score of 90 out of 100, therefore their scores were normalised to a maximum of 100 out of 100. This was done to avoid penalising SU that do not have structure data mapped because of the paucity of structure data across the region.

Table 19: Slope type and the susceptibility factors used in this study.

Slope Type	Susceptibility Factor
Cataclinal Slopes	1
Orthoclinal Slopes	0
Anaclinal Slopes	0

7.3.3 TERRAIN

The relative importance of slope angle, aspect, and relief on large-scale landslide susceptibility has been assessed in each geomorphic sub-region through an analysis of the landslide inventory and regional terrain. Slope and aspect rasters were generated in ArcGIS Pro using a 1 m DEM and each landslide and slope unit was assigned a median slope angle and aspect value. Median relief was calculated for each landslide and slope unit by sampling the 1 m DEM and determining the change in elevation within each polygon. For slope angle and relief, the percentage of slope units and landslides were compared to inform the susceptibility factors in each landslide terrain sub-region. For the landslide terrain sub-regions with little (<30 data points) landslide data, the overall regional percentage for each value was used. For aspect, analysis was carried out for the whole region rather than individual geomorphic sub-regions.

SLOPE ANGLE

For slope angle, regional large-scale landslides tended to be more prevalent on slopes between 10°-30° and less prevalent on slopes less than 10° or greater than 30° (Figure 27). Further, slopes with median angles of 10-15° accounted for a large proportion of the regional landslide inventory, probably reflecting the fact that the failed slope will have a lower average slope angle than before failure. To capture thresholds of slope angles that may influence large-scale landslides, a susceptibility factor was applied to each slope angle band based off the landslide inventory. Slopes with median angles of 10-15° received the highest susceptibility factor according to the entire landslide dataset. This process was completed for each individual geomorphic sub-region and summarised in Table 20.

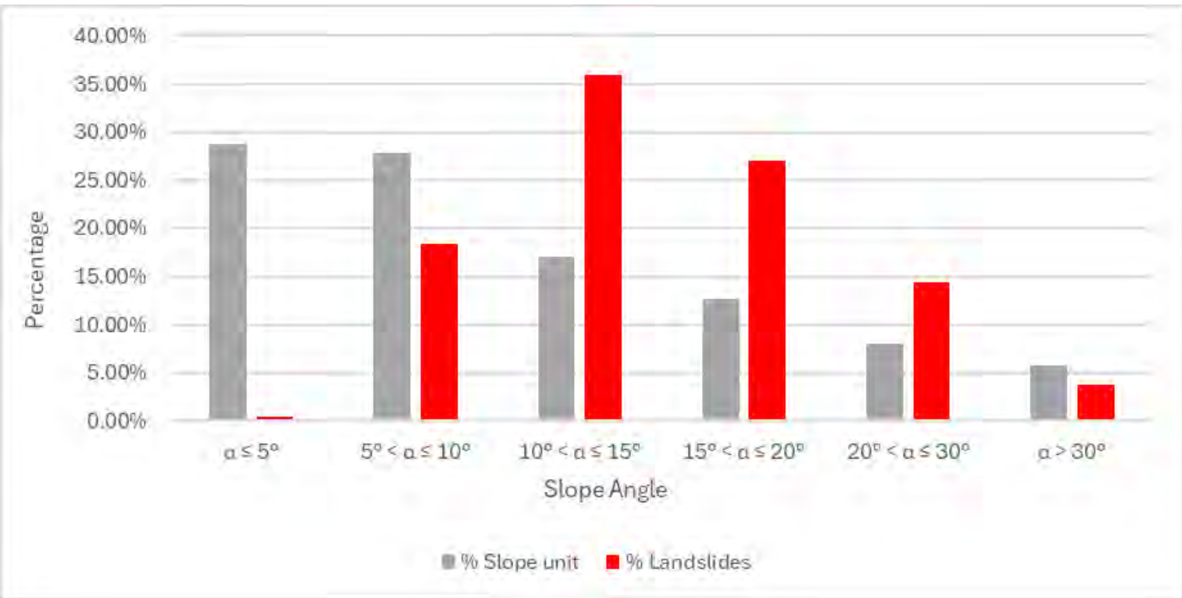

Figure 27: Slope units and large-scale landslide proportions by slope angle in the Auckland Region

Table 20: The susceptibility factor used for each slope angle band in each Geomorphic sub-region.

Geomorphic sub-region	α ≤ 5°	5° < α ≤ 10°	10° < α ≤ 15°	15° < α ≤ 20°	20° < α ≤ 30°	α > 30°
All sub-regions (Figure 27)	0.2	0.3	1	0.8	0.6	0.4
Active Dunes	0.2	0.3	1	0.8	0.6	0.4
Auckland Volcanic Field	0.2	0.3	0.4	0.6	0.8	1
Awhitu	0.2	0.8	1	0.6	0.3	0.4
Hauraki Islands	0.2	0.3	1	0.8	0.6	0.4
Northland Allochthon	0.3	0.4	1	0.6	0.8	0.2
South Auckland Volcanic Field	0.2	0.3	1	0.8	0.6	0.4
Southern Landslide Zone	0.4	0.3	0.2	0.6	1	0.8
Waipapa / Hunua	0.4	0.6	1	0.8	0.3	0.2
Waitakere	0.2	0.3	1	0.8	0.6	0.4
Waitemata Lowlands	0.2	0.3	1	0.8	0.6	0.4
Waitemata Highlands	0.2	0.3	1	0.8	0.6	0.4

ASPECT

For aspect, regional large-scale landslides tended to be more prevalent on slopes facing S, SE, and E and less prevalent on slopes facing N, SW, and W (Figure 28), although the relative paucity of north-facing landslides may be influenced by bias in the landslide inventory mapping which may have under-represented some aspect directions. Susceptibility factors for each aspect direction were selected based on the landslide inventory analysis and literature review (Brabhaharan et al., 1994; Bloom, 2022; Corominas, et al., 2014; WSP, 2023; WSP, 2024) (Table 21).

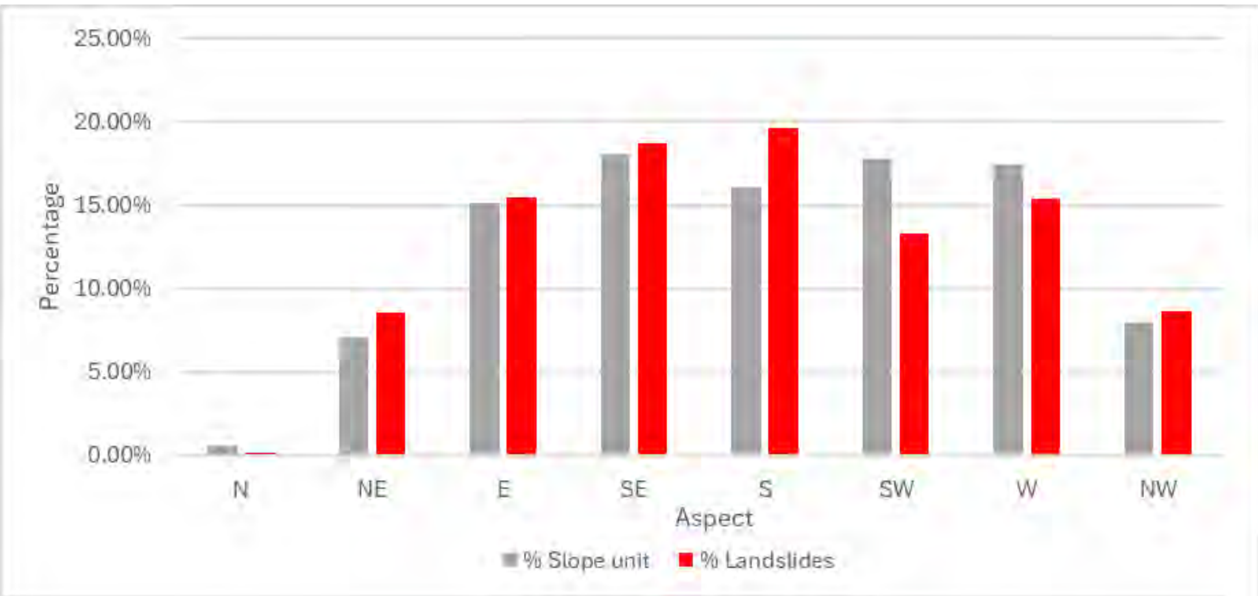

Figure 28: Slope units and large-scale landslides by aspect in the Auckland Region

Table 21: The susceptibility factor used for each aspect direction in this study.

Aspect	Susceptibility Factor
N (337.5-22.5)	0.2
NE (22.5-67.5)	0.4
E (67.5-112.5)	0.6
SE (112.5-157.5)	0.8
S (157.5-202.5)	1
SW (202.5-247.5)	0.8
W (247.5-292.5)	0.6
NW (292.5-337.5)	0.4

RELIEF

For relief, regional large-scale landslides tended to be more prevalent on slopes with 20 m to 60 m of relief and less prevalent on slopes with less than 20 m or greater than 60 m of relief (Figure 29). Further, slopes with relief of 20 m to 40 m accounted for a larger proportion of the landslide inventory. Based on Figure 29 a susceptibility factor was assigned to each relief band (Table 22). Susceptibility factors for relief were relative to the proportion of slope unit and landslide area within each relief band. This process was completed for each geomorphic sub-region and summarised in Table 22.

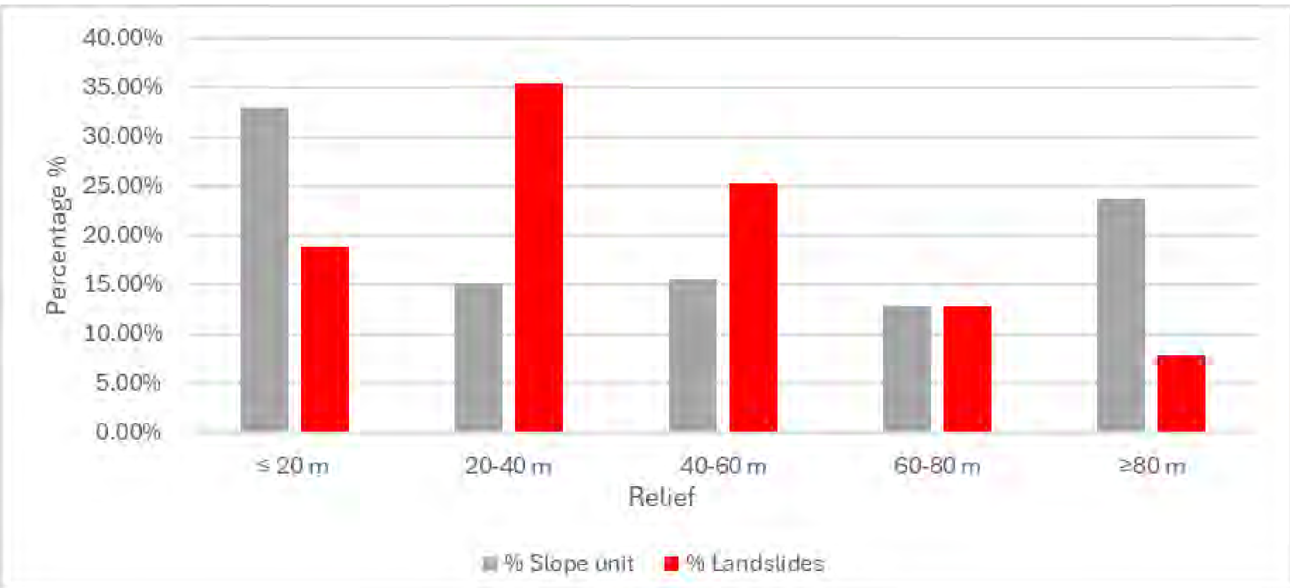

Figure 29: Slope units and large-scale landslides by relief in the Auckland Region

Table 22: The susceptibility factor used for each relief band in each Geomorphic sub-region.

Geomorphic sub-region	≤ 20 m	20-40 m	40-60 m	60-80 m	≥80 m
All sub-region (Figure 24)	0.4	1	0.8	0.6	0.2
Active Dunes	0.4	1	0.8	0.6	0.2
Auckland Volcanic Field	0.4	1	0.8	0.6	0.2
Awhitu	0.4	1	0.8	0.6	0.2
Hauraki Islands	0.4	1	0.8	0.6	0.2
Northland Allochthon	0.4	1	0.8	0.6	0.2
South Auckland Volcanic Field	0.4	1	0.8	0.6	0.2
Southern Landslide Zone	1	0.8	0.6	0.4	0.2
Waipapa / Hunua	0.6	1	0.8	0.4	0.2
Waitakere	0.2	0.6	1	0.8	0.4
Waitemata Lowlands	0.2	1	0.8	0.6	0.4
Waitemata Highlands	0.2	0.8	1	0.6	0.4

7.3.4 HYDROLOGY

The stream order of each slope unit was determined using the River Environment Classification (REC2) developed by NIWA (NIWA, 2019). The REC2 assigns an order (1-8) for each stream and river in New Zealand based on size, where order 1 represents the smallest streams. As slope units are bounded by drainage lines, each slope unit was assigned a stream order from the stream or river along its lower boundary. Streams at the toes of slopes may contribute to landslides, however, this interaction is likely to be complex and dependent on other factors such as slope angle. Streams flowing down a slope might also influence groundwater within and stability of large landslides. For the purposes of this study, it is assumed that slopes associated with a higher stream order and slope angle are more susceptible to large-scale landslides, while slopes with a lower stream order and lower slope angle are less susceptible. Table 23 displays the susceptibility factor used for each stream order. To account for slope angle, the slope angle score was also considered.

Table 23: The susceptibility factor used each stream order.

Stream Order	Susceptibility Factor
1	0.5
2	0.6
3	0.7
4	0.8
5	0.9
6	1

7.3.5 LANDSLIDE COUNT

For landslide count, if a landslide was mapped within a SU, it is assumed that, that SU is more susceptible to further large-scale landslides. For all other SU that do not have a current mapped landslide there is a lower susceptibility for further large landslides. Table 24 shows the susceptibility factor for SU with and without landslides.

Table 24: The susceptibility factor used for landslide count.

Landslide Count	Susceptibility Factor
0	0.5
>=1	1

7.3.6 OVERALL FACTOR WEIGHTINGS

This study utilised the Analytical Hierarchy Process (AHP) to systematically assess landslide susceptibility factor weightings. A hierarchical structure of criteria and alternatives is established, with each criterion representing factors for landslide susceptibility from Table 25. Pairwise comparisons were conducted to determine the relative importance of each factor, as well as assigning numerical values between 1 to 9 based on significance: 1 means equal importance of the two factors being compared, and 9 means extreme importance where one factor over another is of the highest possible order of affirmation. The result provided a weighted ranking of the 8 factors.

The AHP results show that geology, structure, and slope angle are considered to be the most critical factors, where relief, aspect and stream order are considered to have the lowest significance. These were then rounded and modified based on data and level of confidence of the factor (Table 25). Slope angle and relief factors are both derived from the DEM and show some correlation in our dataset. However, this is not a strong relationship and hence using both factors in the analysis is not considered to affect results (Figure 30).

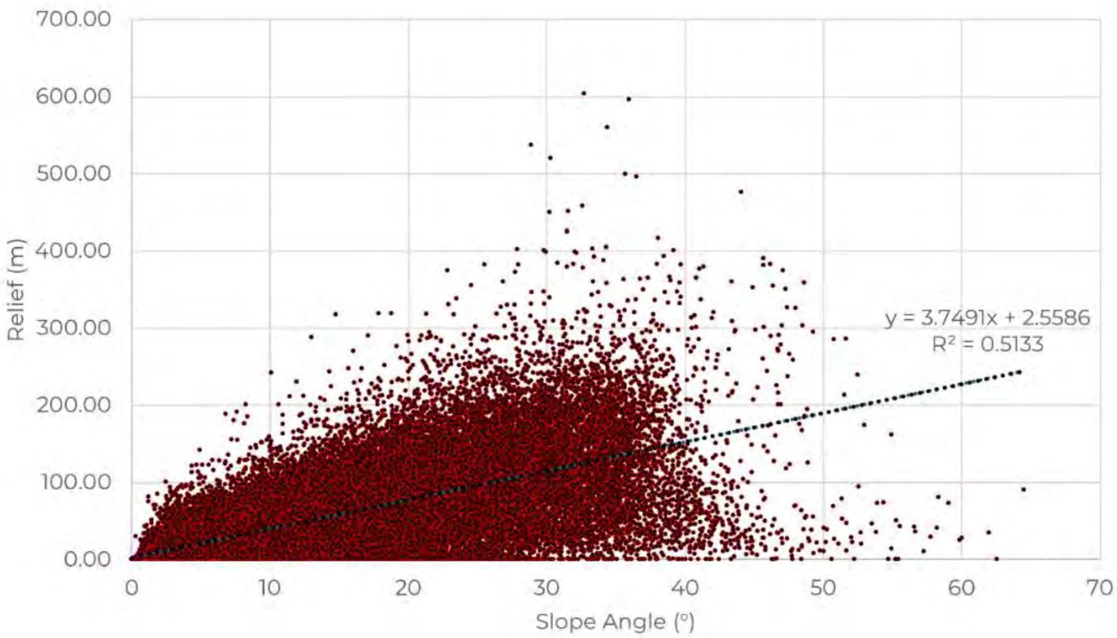

Figure 30: Correlation between slope unit relief and slope angle.

Initially weightings from the AHP were used, however, due to gaps in input datasets (especially structural geology and landslide inventory), factor weightings for structure and landslide count were decreased. The weighting of the other factors, where input datasets were more complete (i.e. relief and stream order), were increased to offset this. To reflect the degree of uncertainty, final weightings were rounded to the nearest 5 points.

Table 25: Landslide susceptibility factor weightings, showing AHP results and final weightings.

Factor	AHP Weighting Results	Adjusted Susceptibility Weighting
Structure	17.2	10
Slope	18.5	20
Aspect	9.1	10
Relief	9.9	15
Stream Order	5.5	10
Landslide Count	17.5	15
Geomorphology & Geology	22.2	20

7.4 ANALYSIS AND CLASSIFICATION

The total landslide susceptibility scores for each SU were derived by multiplying the susceptibility factor value (F_v) by the corresponding factor weighting (W_w) and then summing up the products of the above to derive the final susceptibility score.

$$Landslide\ Susceptibility\ Score = \sum(F_V \times W_w)$$

Landslide susceptibility scores for each SU are plotted in Figure 31, showing the distribution of all the SU as well as the susceptibility score for mapped landslides, to show the increasing proportion of the landslide population with increasing susceptibility score.

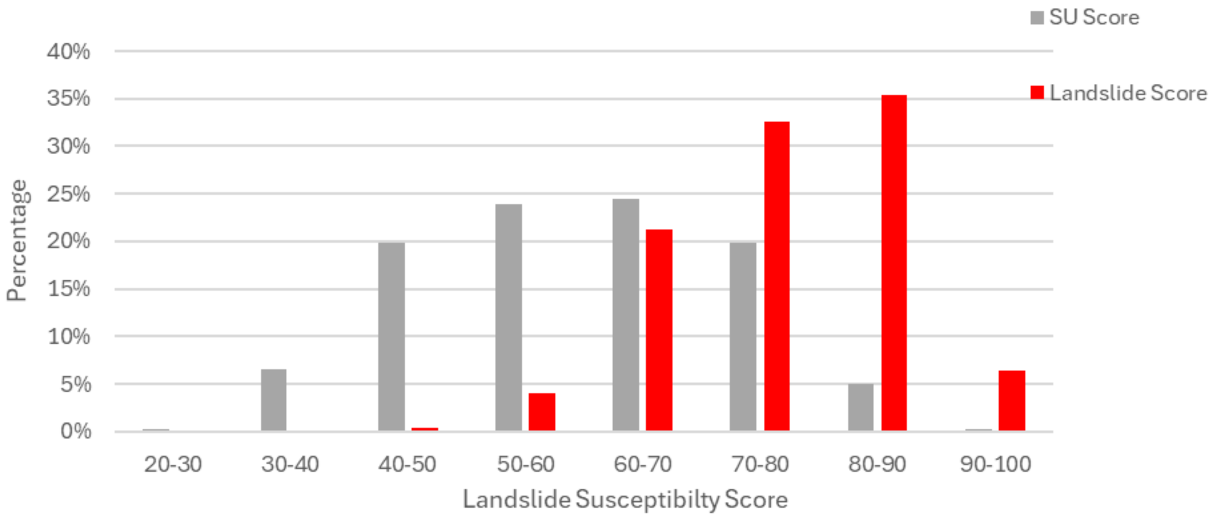

Figure 31: Distribution of Slope Unit susceptibility scores in the Auckland Region, showing all SU scores (grey bars) and susceptibility scores for mapped landslides (red bars).

The method for classifying the large-scale landslide susceptibility is consistent with that used for the shallow landslides. However, due to the qualitative nature of the large-scale landslide susceptibility assessment, an altered approach was taken. Confusion matrices, which quantify the counts of True Positive, True Negative, False Positive and False Negative classification results, were created at various cut-off values of susceptibility score. These allow more detailed analysis of model performance than simply observing the proportion of correct classifications (i.e., True Positive or True Negative). The accuracy of landslide occurrence classification was then assessed using the confusion matrices. The calculated cut-off for each sub-region identifies the large-scale susceptibility model with the highest accuracy in predicting the presence or absence of a mapped landslide within a given slope unit. The highest accuracy cut-off values are used to define the boundary between 'susceptible' and 'not-susceptible' classes; this is taken as the boundary between the low and moderate susceptibility classes for all sub-regions other than Awhitu, Hauraki Islands and Waitakere Ranges. Jenks natural breaks are used to divide the predictions below the cut-off value into very low and low susceptibility, and above the cut-off value into the moderate, high and very high susceptibility classes. For the Awhitu, Hauraki and Waitakere sub-regions, the highest accuracy cut-off was used as the boundary between moderate and high susceptibility as this was found to better represent the level of susceptibility based on a review of the geomorphic characteristics and the distribution of mapped landslide features in those three sub-regions. Jenks natural breaks are used to divide the predictions below the cut-off into the very low to moderate classes and above the cut-off into the high and very high classes.

The cut-off values, model accuracies, and susceptibility class boundary values for each sub-region are listed in Table 26.

Table 26: Susceptibility classification according to slope unit score in each geomorphic sub-region.

Geomorphic Sub-region	Highest accuracy cut-off		Susceptibility class boundaries				
	Susceptibility Score	Accuracy	Very low	Low	Moderate	High	Very high
Active Dunes	70	83.0%	≤ 55	≤ 70	≤ 74	≤ 77	> 77
Auckland Volcanic Field	46.3	93.4%	≤ 36.6	≤ 46.3	≤ 50.5	≤ 59.4	> 59.4
Awhitu	71.6	72.8%	≤ 48.9	≤ 61.3	≤ 71.6	≤ 75.5	> 75.5
Hauraki Islands	66	84.1%	≤ 41.3	≤ 52.3	≤ 66	≤ 71.5	> 71.5
Northland Allochthon	79.6	92.2%	≤ 63.5	≤ 79.6	≤ 83.3	≤ 87.7	> 87.7
Southern Landslide Zone	64.6	76.1%	<57.2	≤ 64.6	≤ 73	≤ 82.7	> 82.7
South Auckland Volcanic Field	51.8	90.0%	<42.4	≤ 51.8	≤ 59.4	≤ 67.2	> 67.2
Hunua Ranges	66.3	80.9%	<56.5	≤ 66.3	≤ 70.9	≤ 76.1	> 76.1
Waitakere	61.7	49.4%	<39.7	≤ 49	≤ 61.7	≤ 63.8	> 63.8
Waitemata Highlands	69.7	71.8%	<56.3	≤ 69.7	≤ 75.1	≤ 81.3	> 81.3
Waitemata Lowlands	54.3	92.7%	<41.5	≤ 54.3	≤ 61	≤ 68.5	> 68.5

The proportions of land area and landslide population within the slope units for each of the susceptibility classes across the region are summarised in Table 27.

Table 27: Comparison of large scale landslide susceptibility class areas to landslide inventory areas within the slope units

Susceptibility class	Study area		Slope unit landslide inventory			
	Area in class (km²)	Proportion of total area of region	Area of landslides in class (km²)	Proportion of total area of landslides	Proportion of total area of class	Proportion of total area of region
Very Low	1,201	25%	4	1%	0.3%	0.1%
Low	1,927	39%	37	13%	2%	0.8%
Moderate	893	18%	44	15%	5%	0.9%
High	525	11%	64	22%	12%	1.3%
Very High	344	7%	139	48%	40%	2.8%

7.5 LARGE-SCALE LANDSLIDE SUSCEPTIBILITY MAP

Figure 32 displays the large-scale landslide susceptibility map for the Auckland Region. Each slope unit in the region has been assigned a susceptibility classification (very low to very high). To capture uncertainty, slope units have been classified as either lower confidence or higher confidence. Higher confidence slope units are those where structural data or landslide data was available when calculating susceptibility.

The large-scale landslide susceptibility assessment indicates that the Auckland Region is prone to large-scale landslides, with certain areas being more susceptible than others. The large-scale landslide analysis used existing landslide data to identify areas with similar geological and geomorphological conditions that may be susceptible to landslides. Sub-regions assessed to have the highest large-scale landslide susceptibility are the Southern Landslide Zone, Waitemata Highlands and Northland Allochthon. Together, these areas account for 53% of SU across the region with high to very high large-scale landslide susceptibility.

Regions assessed to have lower susceptibility to large-scale landslides were the Waitemata Lowlands, Auckland Volcanic Field, and South Auckland Volcanic Field. Together, these areas account for 43% of SU with very low large-scale landslide susceptibility. These sub-regions consist of relatively low-lying and gentle (<5°) slopes, with low relief, and north facing slopes. However, localised areas with higher slope angles such as the volcanic cones resulted in higher susceptibility scores, ranging from low to moderate, which may overestimate the true susceptibility for the unweathered volcanic rocks underlying those slopes.

Land classified as low landslide susceptibility cannot be confirmed to have no potential land instability given the regional scale of the study and the input datasets used.

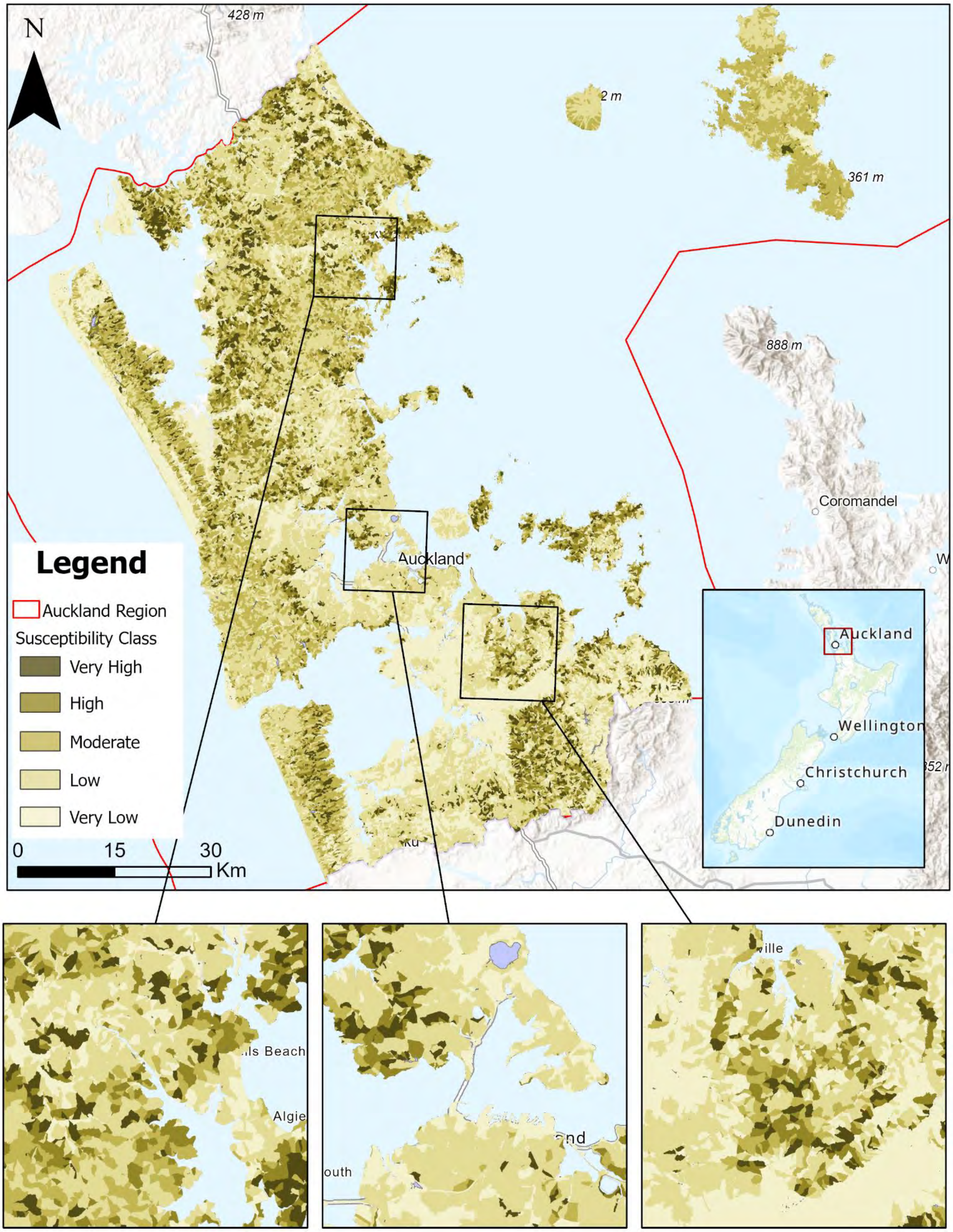

Figure 32: Large-scale landslide susceptibility map with inset maps showing Warkworth, Auckland central, and the SLZ.

7.6 LIMITATIONS AND UNCERTAINTIES

Limitations of the large-scale landslide mapping are discussed previously in Section 5.3. This section will discuss limitations of the large-scale susceptibility methodology and map output.

SCALE OF ASSESSMENT

The landslide susceptibility mapping completed in this study represents a desk-based, region-wide assessment that was carried out from examination of remotely sensed data including LiDAR and aerial imagery, along with regional-scale datasets. The susceptibility analysis was undertaken using geomorphic slope units as the mapping basis. No access was gained to properties, and site-specific stability assessments have not been undertaken. Property owners and developers should seek independent advice on land stability at their particular property when considering development or the existing level of slope instability hazard.

HUMAN BIAS

The extent and level of detail within the available landslide inventory was insufficient across the Auckland Region to represent all the geomorphic sub-regions equally. A heuristic approach was adopted using assignment of factor weightings based on a review of past studies, local experience, and statistical assessment of the landslide inventory in combination with an analytic hierarchy review of pairs of factors. Because the heuristic method involves judgement-based decisions, there may be bias introduced during factor selection and weighting.

SLOPE UNITS

Automatic subdivision of landscapes into hillslopes (Slope Units) has some uncertainties. The accuracy of Slope Units (SU) depends on the resolution of the DEM, as well as the choice of parameters such as maximum and minimum area thresholds. The smaller the maximum area threshold set by the user; the larger number of SU will be obtained. The user will determine what is the most useable threshold for scale of an area of interest. Other thresholds such as flow accumulation are also set by the user that will determine the resolution of the SU.

These thresholds affect the geometry of the SU. For example, when drainage lines do not bisect a catchment or gully completely, the resulting SU may not accurately reflect the topographical and hydrological divides. This may lead to SUs that are too large and do not represent the finer- scale terrain variability. The user-defined thresholds settings are subjective, and professional judgement is necessary, therefore reproducibility of the extracted SU can be difficult.

Areas that can be affected by these uncertainties are areas with significant breaks in slope. SUs as a result may have multiple inclined and flat areas. Costal cliffs are an example of this, where a SU can include the cliff top, cliff crest, and the cliff face. This therefore includes an uncertainty with SU factors such as slope, aspect, and relief, where the median of these factors was used for the factor scoring.

LANDSLIDE INVENTORY

The large-scale landslide inventory collated for this study consists of previously published landslides and terrain features, as well as mapping of features specifically for this study. The landslide inventory is based on the best information available, and the new mapping carried out for this study was targeted on parts of the region where few landslide features had been mapped previously. However, given the large area and varied geology of the Auckland Region, the inventory is not comprehensive and there will be areas that are under-represented in the inventory which will consequently affect the SU scores used to determine the susceptibility classes. To mitigate this a number of factors were used and landslides present is only one factor.

LANDSLIDE MECHANISMS AND TRIGGERS

The available landslide inventory also does not include sufficient information on the triggers or mechanisms of slope movement on the scale of the region to differentiate different failure mechanisms within the susceptibility mapping. The age of the mapped landslide features is also unknown, and therefore the triggers for landslides such as climatic, seismic or hydrological factors cannot be determined from the available data.

LANDSLIDE RUNOUT

The large-scale landslide inventory consists of landslide features that extend over most of or full height of slopes, observed in the aerial photography and maps as geomorphological features. These features therefore represent accumulated slope deformation within source and deposition areas, but do not necessarily encompass the full deposition, run-out or regression areas.

7.7 FUTURE UPDATES

The large-scale susceptibility map is intended to be dynamic and able to incorporate future research including landslide inventories, regional topographical and geological data, and published literature. Future landslide inventories can be incorporated into the analysis and may change landslide susceptibility factor values. Additions to the database of regional structural geological measurements would also be valuable additional data to include in future updates.

Future enhancement of the large-scale susceptibility map could be provided through more detailed research into identified high susceptibility areas such as the Waitemata Highlands north of Auckland City and Northland Allochthon. This could include detailed desktop and field mapping, assessment of structural geological data, and local susceptibility assessment. The findings of the detailed assessment would then help strengthen or update the regional scale assessment of landslide susceptibility factors used in this study.

8 APPLICATIONS FOR THE STUDY

8.1 INTENDED USE AND LIMITATIONS

8.1.1 INTENDED USE

This study was undertaken at a regional scale and the maps are for high-level land-use planning purposes. It would also inform consideration of the resilience of infrastructure networks at a high level, supplemented by specific assessment, and use in broad level consideration of emergency response planning.

8.1.2 OTHER APPLICATIONS

Brabhaharan (2000, 2010) provides information on the different levels and grades of zonation and their application in management of the risk associated with natural hazards. In addition to land use planning, they outline their uses for a range of other applications such as research into the natural hazards, providing information for land and residential development, planning of lifeline infrastructure assets and assessment of the resilience of existing infrastructure, assessing the risk to the built environment and communities, as well as planning for managing the risk which includes emergency management. Brabhaharan (2010) also provides practical examples of application of the natural hazard susceptibility maps for a variety of such applications throughout New Zealand. Therefore, the landslide susceptibility maps, though primarily prepared for planning use, can be used in a wide variety of ways to reduce the natural hazards risk to communities and enhance the resilience of lifeline infrastructure.

Brabhaharan and Mason (2015) and Mason et al (2015) provide examples of how the maps can be used in planning to achieve resilient communities and in the development of risk management planning regulations to mitigate landslide risk. Mason and Brabharan (2013) describe the use of hazard mapping to inform urban growth strategies that take into consideration the natural hazards and ensure future sustainability. These papers provide a wealth of information and practical examples on how the landslide susceptibility maps can be used to enhance the resilience and mitigate risks to communities.

8.1.3 NOT FOR USE IN SITE SPECIFIC HAZARD ASSESSMENT

The maps should not be used for site specific analysis of landslide susceptibility. This is because:

a) The resolution of the data used to develop the maps is not appropriate for site specific use.

b) The landslide inventory data used as the basis for assessing landslide susceptibility is limited.

c) The landslide susceptibility maps do not incorporate the regression or runout / inundation zones that form a part of hazard from landslides. Only the failure source area is considered.

Site-specific conditions, analysis of slope failure likelihood, and consideration of post-failure effects (i.e., landslide runout) are not captured in the susceptibility mapping. These would be required for site-specific analysis of landslide susceptibility, for example for planning new developments or for Resource or Building consents.

8.1.4 SCALE OF THE MAPS

The AGS (2007a) guidelines suggest that scales between 1 : 100,000 and a maximum of 1 : 25,000 are appropriate for susceptibility zoning mapping completed across regional areas (defined as 1,000 km^2 to 10,000 km^2; the Auckland Region is approximately 5,000 km^2). The maps should be used based on these guidelines.

As this is a regional-scale study, we recommend that the mapped susceptibility zones based on this landslide susceptibility study are displayed at scales:

a) No larger (i.e. in more detail) than 1 : 25,000 for the shallow landslide susceptibility maps, and

b) No larger (i.e. in more detail) than 1 : 50,000, for the large-scale landslide susceptibility maps.

8.1.5 DISCLAIMER FOR INCLUSION WITH THE MAPS

A disclaimer should be included on the maps to inform readers:

a) of the scale that they should be viewed at, and that they are for information only and are not intended for assessments of individual properties.

b) that the maps indicate the susceptibility of slopes to failure, but do not include areas where regression or runout may occur.

8.2 RISK REDUCTION MEASURES

Different controls on activities and development can be implemented to manage the risk of landslides to property, life, buildings and lifeline infrastructure in the Auckland Region. The landslide susceptibility maps presented in this study can be used to inform these controls through planning measures.

The implementation of specific risk reduction measures should be based on discussions between Auckland Council planners and geotechnical engineers, to ensure the controls are appropriate.

8.2.1 LAND USE PLANNING

Land use planning can be used to reduce further development in areas of high landslide risk, with a view to limiting the life and property risks and additional costs to communities and enhancing resilience of risks to roads and utilities serving these areas.

Auckland Council should use the landslide susceptibility maps as a screening tool to inform land use planning, urban growth strategies and plan change proposals to manage the landslide risk.

Where land is considered susceptible to landslides, the requirement for a geotechnical assessment by a suitably qualified and experienced geotechnical professional (PEngGeol and/or CPEng) with relevant experience can be implemented as a control by Auckland Council.

As noted above, Brabhaharan and Mason (2015) and Mason et al (2015) provide examples of how the maps can be used in planning to achieve resilient communities and in the development of risk management planning regulations to mitigate landslide risk.

8.2.2 RESILIENCE OF LIFELINE AND INFRASTRUCTURE SYSTEMS

The landslide susceptibility maps could be used as a high-level screening to assess the resilience of Auckland Council and other government or privately owned lifeline networks and infrastructure such as transport, water supply, wastewater, power, communications, etc. They may also be useful for planning the developments of new infrastructure, and for maintenance management.

Practical applications of the use of the natural hazard maps in the management of existing risk to infrastructure as well as in the development of new infrastructure are presented by Brabhaharan (2000 and 2010).

8.2.3 EMERGENCY MANAGEMENT

Landslides cause significant disruption and damage in earthquake and storm events. The maps will be a valuable information resource for lifeline utility providers and the Civil Defence Emergency Management Group to conduct emergency response planning, as it allows analysis of susceptible areas in the event of heavy rainfall or earthquake.

9 CONCLUSIONS

Areas of land within the Auckland Region that are susceptible to landslides have been assessed and mapped in accordance with internationally recognised guidance and local experience. This corresponds to a 'Level A' analysis under the GNS Science (2024) landslide planning guidance. Landslide susceptibility has been assessed on a region-wide scale, considering factors such as geology, slope angle and relief, and the susceptibility zones developed have been calibrated using the available landslide inventory data. Susceptibility maps were produced through analysis and assessment of important factors that make slopes vulnerable to landslides. This was done using logistic regression analysis for shallow landslides and heuristic analysis for large-scale landslides. The input data and methodology used in producing the susceptibility maps are generally in accordance with a 'Basic' level assessment as described in AGS (2007a).

This report presents details of the methods used to produce the accompanying landslide susceptibility maps for both shallow and large-scale landslides for the Auckland Region.

The two sets of maps have been compiled to identify areas of very high, high, moderate, low and very low landslide susceptibility, based on available data. The susceptibility maps are presented in Appendix A. Maps of the input variables used in the analyses are presented in Appendix B.

The region is exposed to a wide range of landslide hazards, with some areas being prone to rapid and first-time failures, whereas others (such in the Allochthon terrain) are prone to slow moving failures and creep-type deformation.

The susceptibility maps show areas of very high or high susceptibility to shallow landslides in areas of steep to very steep hillslopes (particularly around coastal cliffs, bluffs and incised gullies), and in moderate to steep slopes underlain by weak or soft materials. These areas also have a high concentration of past slope instability. Areas of very high or high susceptibility to large-scale landslide features include slopes of higher relief and steeper slope angles where geological conditions such as geological formation and structure coincide with the prevailing hillslope aspect.

Site-specific conditions, analysis of landslide likelihood, and consideration of post-failure effects such as landslide runout or head scarp regression are not captured in the susceptibility mapping. Flat, low-lying areas at the base of hillslopes will be in low susceptibility zones but may still be prone to damage from inundation by landslide debris or debris flows. Similarly, features that may contribute to higher landslide susceptibility but are smaller than the resolution of the grid cells for the shallow susceptibility assessment (such as localised steep slopes) may not be captured in the maps. The susceptibility of specific areas of slope may vary from what is shown on the maps.

The specific hazards and risks posed by landslides at any given location would need to be further assessed with consideration of the landslide potential (of which susceptibility is a key factor) as well as the consequential effects of landslide runout and head scarp regression.

The landslide susceptibility maps provide valuable hazard information to inform land use planning, urban growth strategies and plan change proposals, to ensure that development is discouraged in areas of high susceptibility (or managed through design) and instead directed to areas of lower susceptibility. The maps also provide information to understand and plan for the impacts on the resilience of infrastructure networks and planning of emergency response and recovery after severe storm events.

10 RECOMMENDATIONS

Based on the results of the study, we make the following recommendations for consideration:

Application of the outputs of the study

1 The shallow landslide susceptibility maps are used at a scale no greater than 1 : 25,000, and large-scale landslide susceptibility maps are used at scales no greater than 1 : 50,000. A disclaimer should be included that the maps should not be displayed or considered at a larger scale, potentially as overlay text on the map.

2 The landslide susceptibility maps are used by Auckland Council to inform land use planning, urban growth strategies and plan change proposals, to ensure that development is discouraged in areas of high hazard and instead directed to areas of lower hazard. Consideration should be given to the type of landslide hazards, such as shallow and large-scale landslides and rapid, slow moving and creep deformation, given the wide range of landslide hazards, to which the region is exposed to.

3 The landslide susceptibility maps are used to develop district plan rules, assessment of resource consent applications and when considering building consents, to ensure that the landslide risks to development and the community are managed appropriately. The advice of competent geotechnical engineers should be sought to facilitate these actions.

4 The landslide susceptibility assessment is used as the basis for assessment of the resilience of Council and other government or privately owned lifeline systems and infrastructure such as transport, water supply, wastewater, power, communications etc. The maps would also be useful for planning the development of new infrastructure, and for maintenance management.

5 The landslide susceptibility maps are used for emergency response planning by lifeline utility owners and civil defence and emergency management groups to plan their response.

Opportunities for future enhancements

6 Extend the shallow landslide susceptibility assessment to consider the consequences of failure and identify areas of potential regression and run out. This is important to show areas that may be affected by landslide hazard outside the steep slopes where initial failures occur.

7 Improve the resolution of the maps for targeted priority areas, using higher resolution data than the 32 m resolution grid cells used in this study. This would provide much better resolution of different levels of susceptibility, particularly where there are sharp changes in hazard over short distances, such as along coastal cliffs and other boundaries.

8 Review and update the landslide susceptibility maps periodically, and when there is a step change in data available or need. For example, climate change and increased frequency of severe weather events could induce more landsliding, and the degree of landslide susceptibility. Additional data from future landslides could be used to refine the susceptibility maps

9 Ongoing data collection and geotechnical investigations are implemented, to improve understanding of the distribution, impacts and controlling factors of landslides in targeted areas of the region. Such measures could include:

   a A programme of landslide data collection for Auckland Council maintenance staff and contractors to capture systematic records of failures as they occur. The data collected could include information on the location, type and size of failure, using data capture tools.

b Periodic investigation of individual landslides, to advance the understanding of the ground and groundwater conditions at the time of failure and following failure (using instrumental monitoring). This should include assessment and documentation of relationships between the failure mechanism, landslide volume, runout characteristics, and correlation with rainfall data to improve the understanding of slope behaviour in response to rainfall triggers.

c A programme of groundwater monitoring and soil permeability testing in areas susceptible to landslides, to enhance the understanding of the groundwater regime in the soils close to slopes. This could be extended to investigate the effects of surface water infiltration on slope instability, to assess the risks associated with stormwater soakage and overland flow in critical areas.

LIMITATIONS

This report ('Report') has been prepared by WSP New Zealand Limited ('WSP') exclusively for Auckland Council ('Client') in relation to Auckland Council Landslide Susceptibility Methodology Report ('Purpose') and in accordance with the Auckland Landslide Susceptibility Study Statement of Works Geotechnical Panel CW201341 agreement with Auckland Council 27/06/2023 ('Agreement'). The findings in this Report are based on and are subject to the assumptions specified in the Report and the Auckland Landslide Susceptibility Study – Stage 1 Methodology 1-C1875.24 17/10/2023. WSP accepts no liability whatsoever for any use or reliance on this Report, in whole or in part, for any purpose other than the Purpose or for any use or reliance on this Report by any third party.

In preparing this Report, WSP has relied upon data, surveys, analyses, designs, plans and other information ('Client Data') provided by or on behalf of the Client and publicly available data. Except as otherwise stated in this Report, WSP has not verified the accuracy or completeness of the Client and public Data. To the extent that the statements, opinions, facts, information, conclusions and/or recommendations in this Report are based in whole or part on the Client Data, those conclusions are contingent upon the accuracy and completeness of the Client Data. WSP will not be liable for any incorrect conclusions or findings in the Report should any Client Data be incorrect or have been concealed, withheld, misrepresented or otherwise not fully disclosed to WSP.

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APPENDIX A – LANDSLIDE SUSCEPTIBILITY MAPS

Figure:

Shallow scale landslide susceptibility

Prepared For:

Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by: wsp

Date: 04/03/2025

Sheet: 1 of 5

Legend:

Auckland Region

Sub-region Boundary

Susceptibility Class

- Very High
- High
- Moderate
- Low
- Very Low

Notes:

This map is intended to be viewed with the Auckland Landslide Study Technical Report. This study is a region-wide assessment and does not account for property-specific ground conditions. The recommended scale of usage for this map is 1:100,000

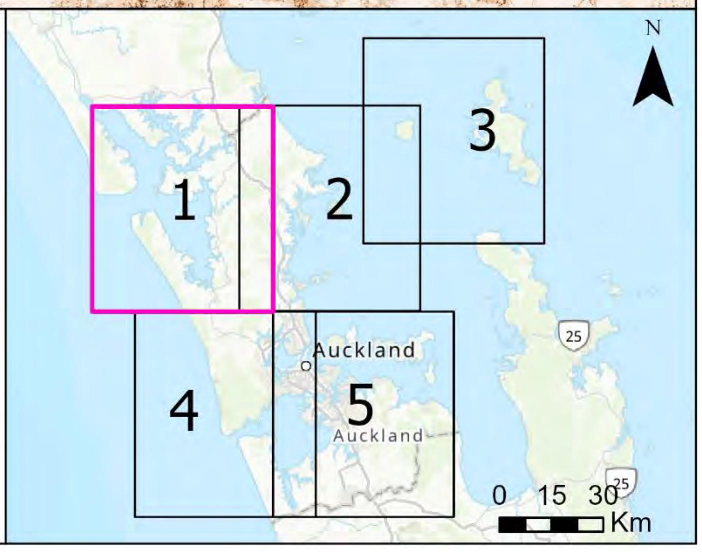
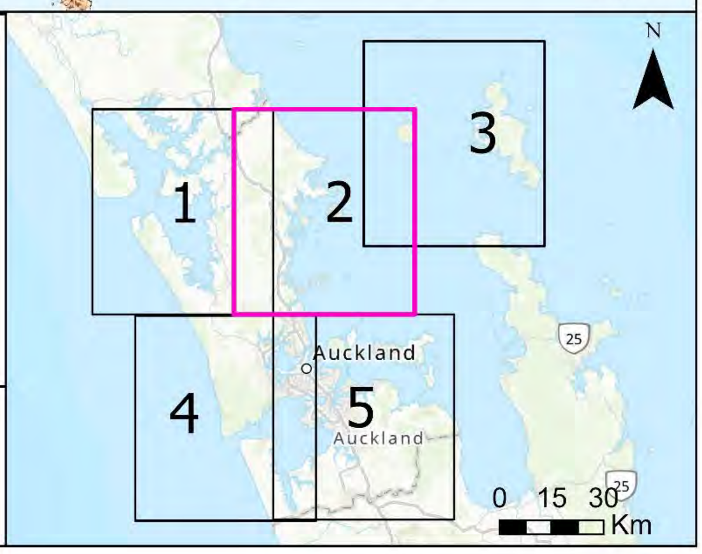


Figure:
Shallow scale landslide susceptibility

Legend:
Auckland Region
Sub-region Boundary
Susceptibility Class
Very High
High
Moderate
Low
Very Low



Prepared For:
Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by: WSP

Date: 04/03/2025

Sheet: 2 of 5

Notes:
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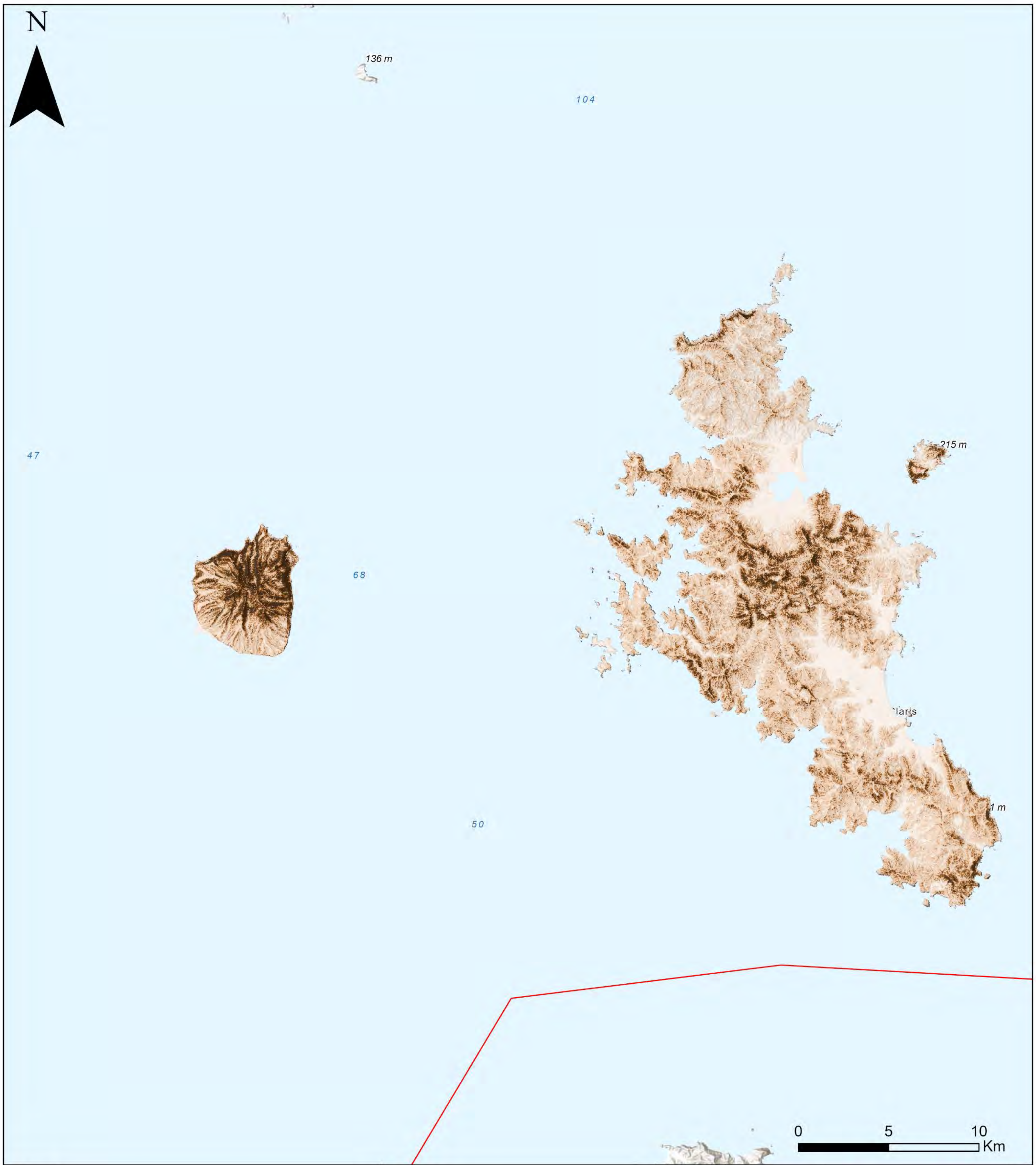


Figure:

Shallow scale landslide susceptibility

Prepared For:

Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by:

Date: 04/03/2025

Sheet: 3 of 5

Legend:

- Auckland Region
- Sub-region Boundary

Susceptibility Class

- Very High
- High
- Moderate
- Low
- Very Low

Notes:

This map is intended to be viewed with the Auckland Landslide Study Technical Report. This study is a region-wide assessment and does not account for property-specific ground conditions. The recommended scale of usage for this map is 1:100,000

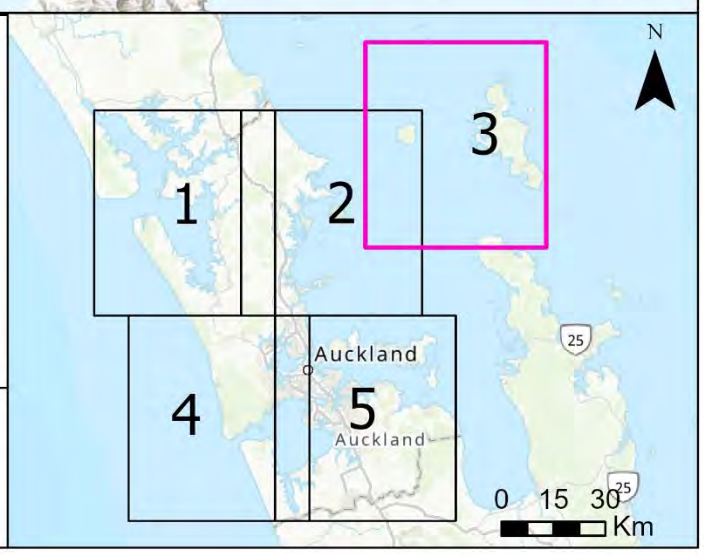


Figure:

Shallow scale landslide susceptibility

Legend:

Auckland Region

Sub-region Boundary

Susceptibility Class

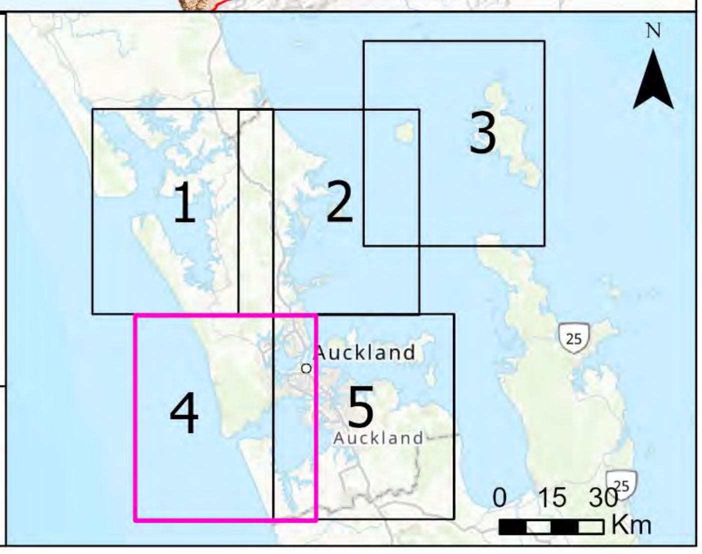
Very High

High

Moderate

Low

Very Low



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Project code: 1-C1875.24

Prepared by:

wsp

Date:

04/03/2025

Sheet:

4 of 5

Notes:

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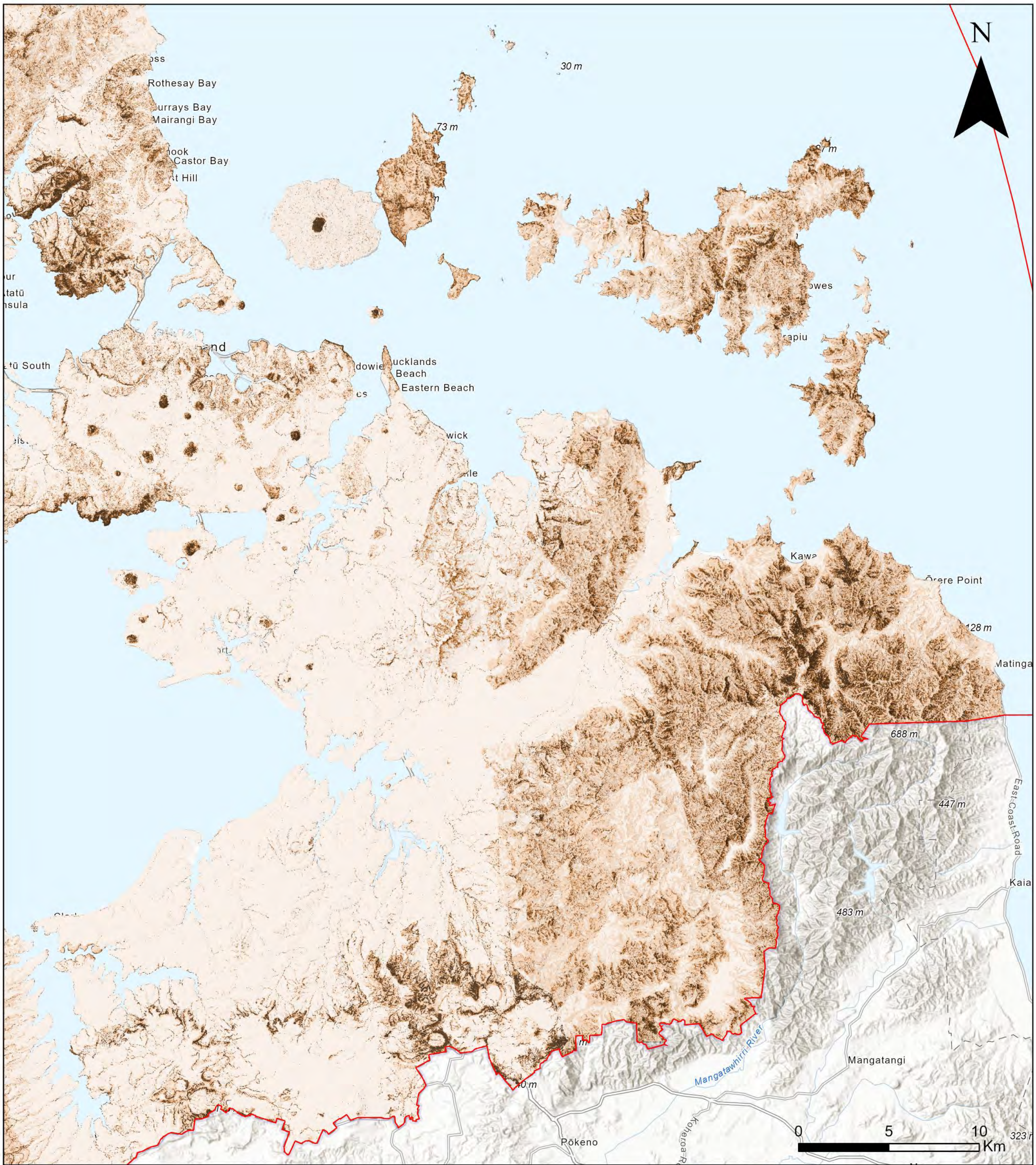


Figure:

Shallow scale landslide susceptibility

Prepared For:

Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by:

wsp

Date:

17/09/2024

Sheet:

5 of 5

Legend:

Auckland Region

Sub-region Boundary

Susceptibility Class

Very High

High

Moderate

Low

Very Low

Notes:

This map is intended to be viewed with the Auckland Landslide Study Technical Report. This study is a region-wide assessment and does not account for property-specific ground conditions. The recommended scale of usage for this map is 1:100,000

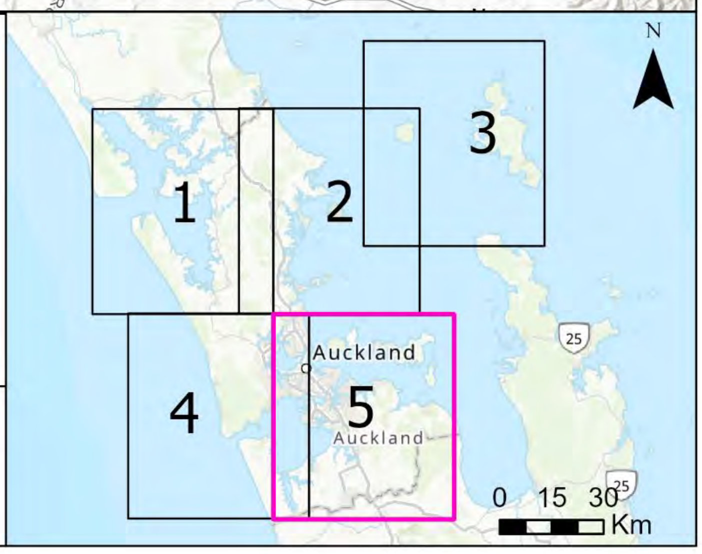


Figure:

Large scale landslide susceptibility

Prepared For:

Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by: WSP

Date: 04/03/2025

Sheet: 1 of 5

Legend:

- Auckland Region
- Sub-region Boundary

Susceptibility Class

- Very High
- High
- Moderate
- Low
- Very Low

Notes:

This map is intended to be viewed with the Auckland Landslide Study Technical Report. This study is a region-wide assessment and does not account for property-specific ground conditions. The recommended scale of usage for this map is 1:100,000

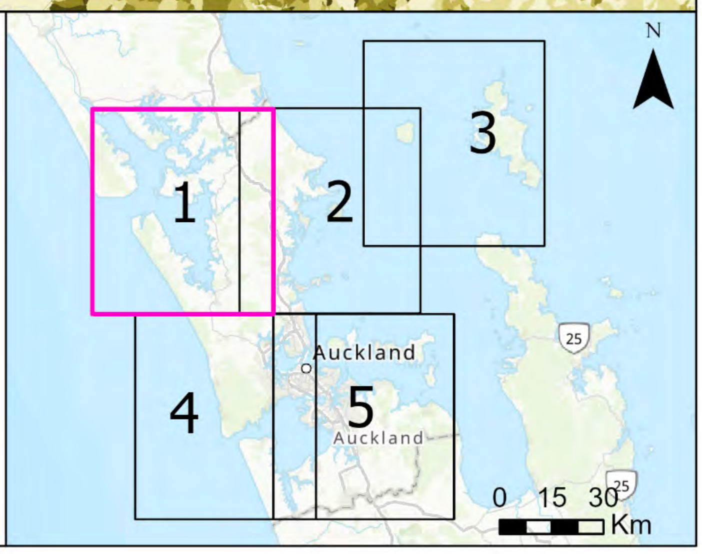
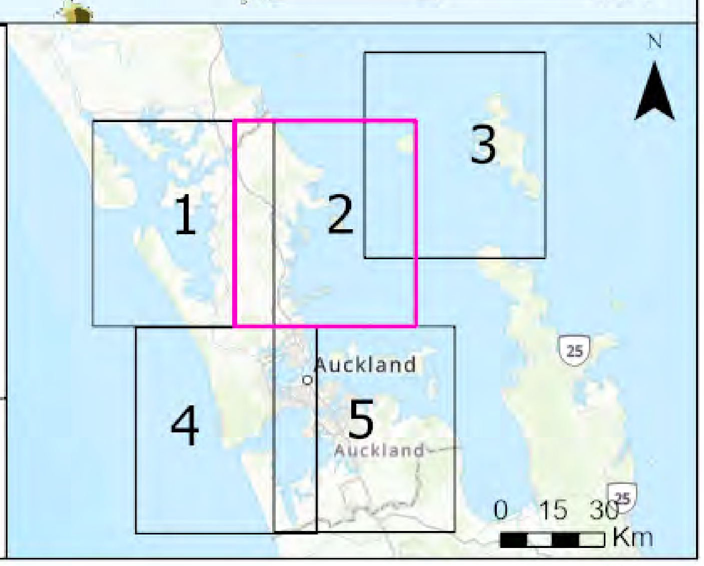


Figure:
Large scale landslide susceptibility

Legend:
Auckland Region
Sub-region Boundary
Susceptibility Class
Very High
High
Moderate
Low
Very Low



Prepared For:
Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by: wsp

Date: 04/03/2025

Sheet: 2 of 5

Notes:
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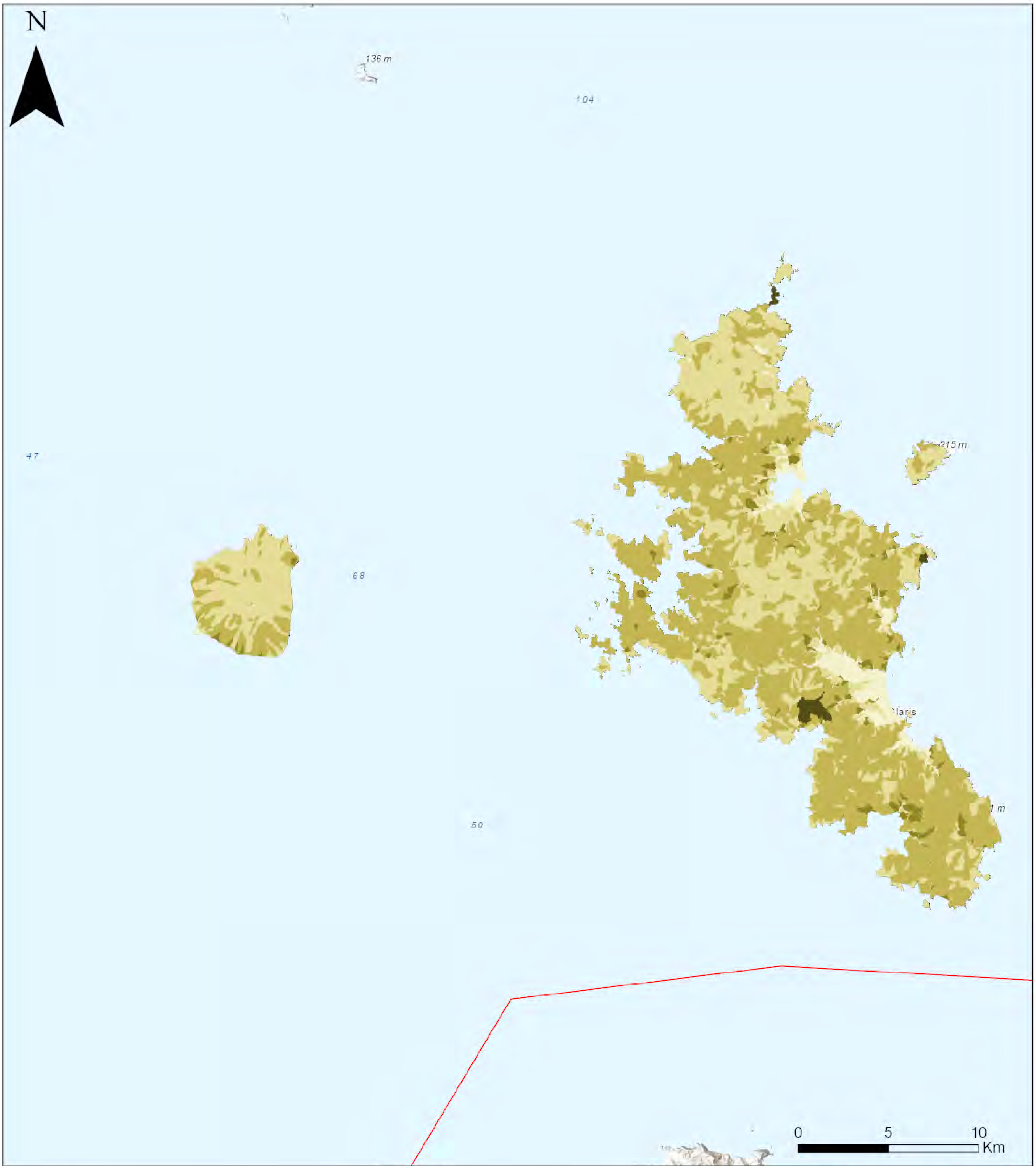
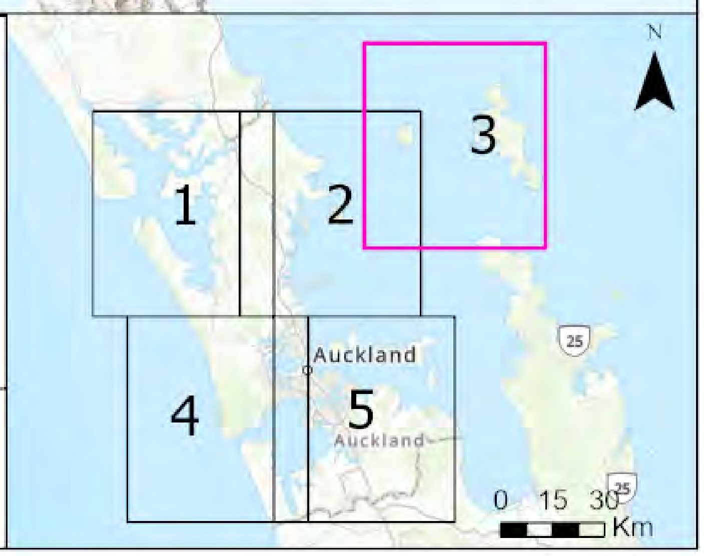


Figure:
Large scale landslide susceptibility

Legend:
Auckland Region
Sub-region Boundary
Susceptibility Class
Very High
High
Moderate
Low
Very Low



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Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by:	**Date:**	**Sheet:**
WSP	04/03/2025	3 of 5

Notes:
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Figure:

Large scale landslide susceptibility

Prepared For:

Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by:

Date: 04/03/2025

Sheet: 4 of 5

Legend:

Auckland Region

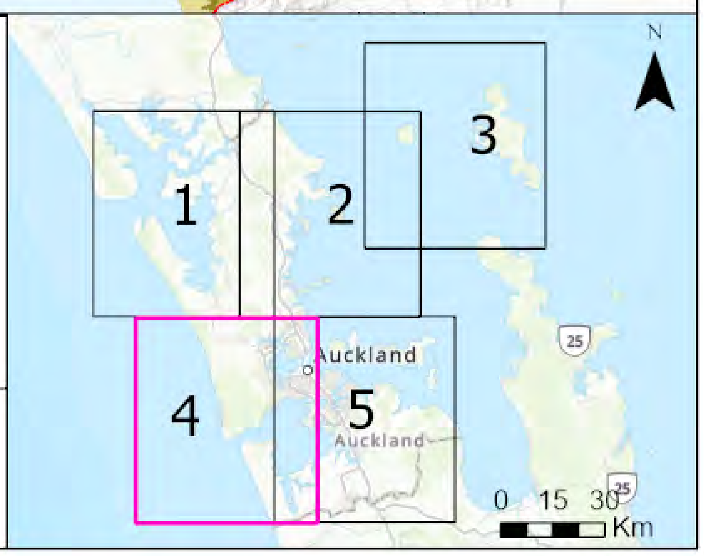
Sub-region Boundary

Susceptibility Class

- Very High
- High
- Moderate
- Low
- Very Low

Notes:

This map is intended to be viewed with the Auckland Landslide Study Technical Report. This study is a region-wide assessment and does not account for property-specific ground conditions. The recommended scale of usage for this map is 1:100,000



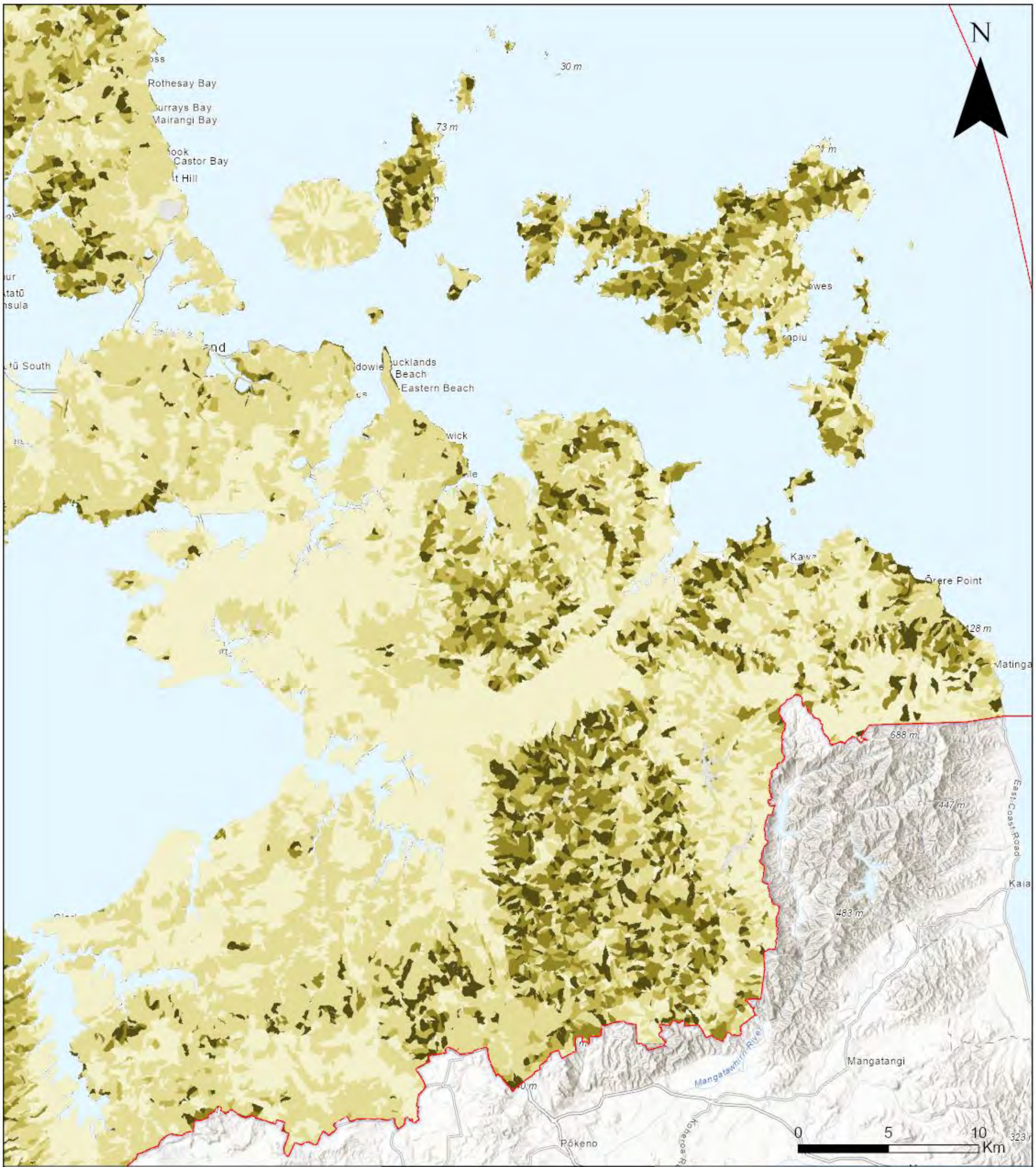


Figure:	**Legend:**
Large scale landslide susceptibility	Auckland Region
	Sub-region Boundary
	Susceptibility Class
	Very High
	High
	Moderate
	Low
	Very Low

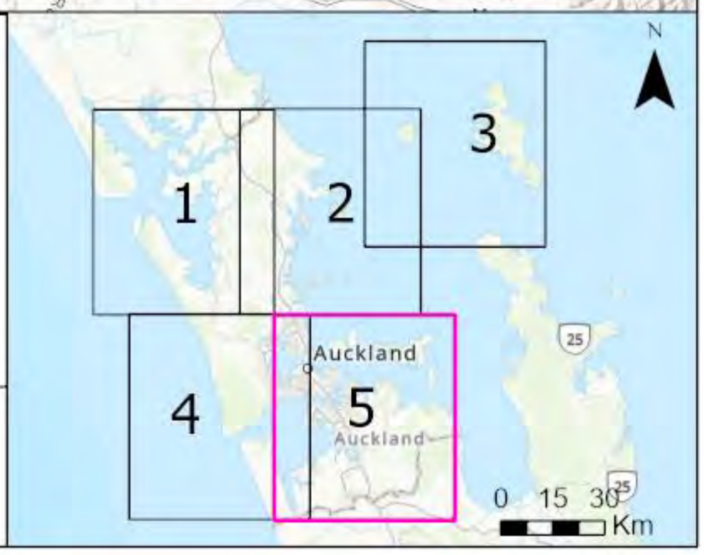
Prepared For:

Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by:	**Date:**	**Sheet:**
wsp	04/03/2025	5 of 5

Notes:

This map is intended to be viewed with the Auckland Landslide Study Technical Report. This study is a region-wide assessment and does not account for property-specific ground conditions. The recommended scale of usage for this map is 1:100,000



APPENDIX B – SUSCEPTIBILITY VARIABLE MAPS

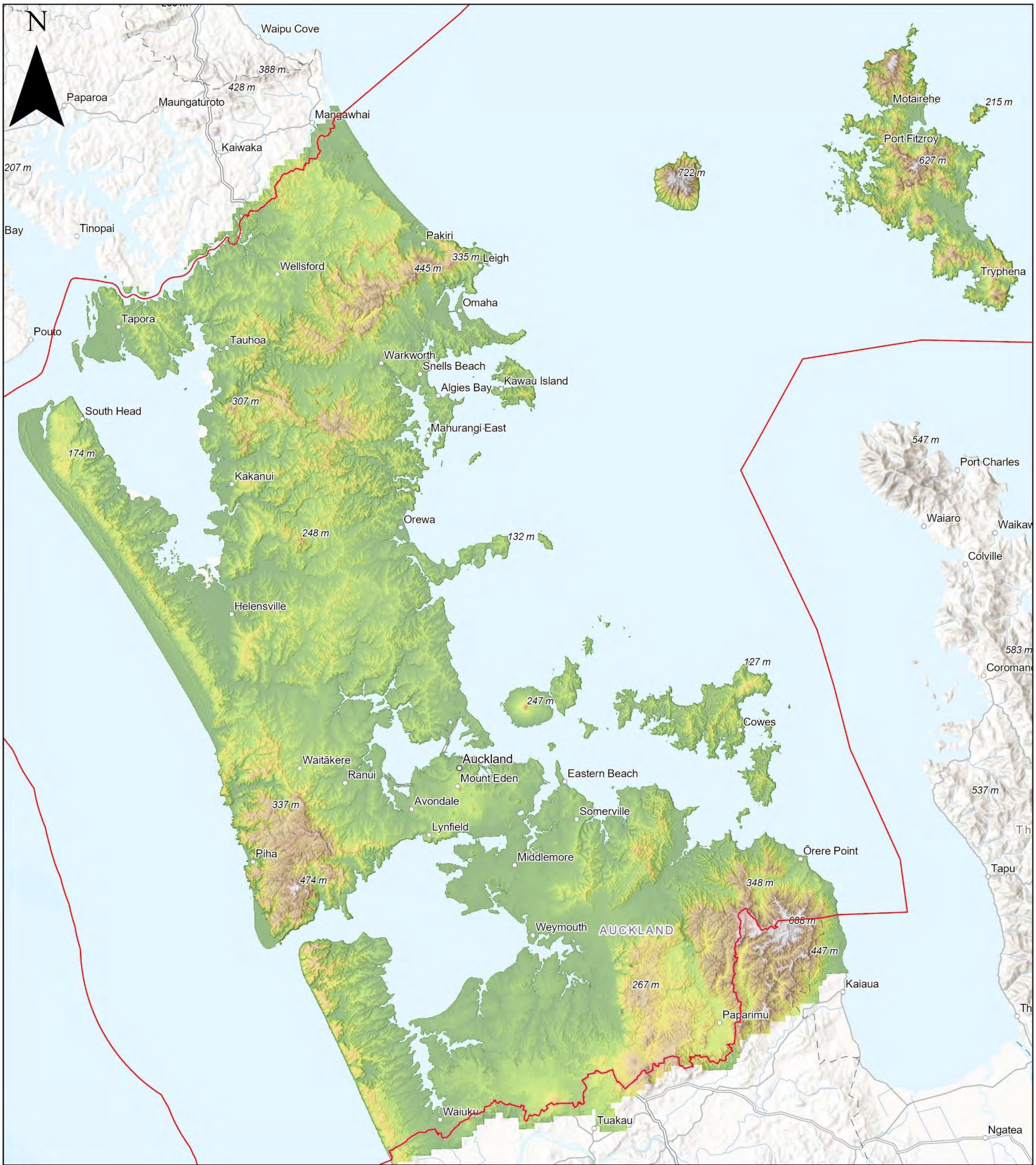


Figure:

Digital Elevation Model (DEM) Raster of the Auckland Region

Legend

Auckland Region

Elevation (m)

721.66

0

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Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by: WSP

Date: 25/06/2024

Sheet: 1 of 1

Notes:
This map is intended to be viewed with the Auckland Landslide Study Technical Report. This study is a region-wide assessment and does not account for property-specific ground conditions.

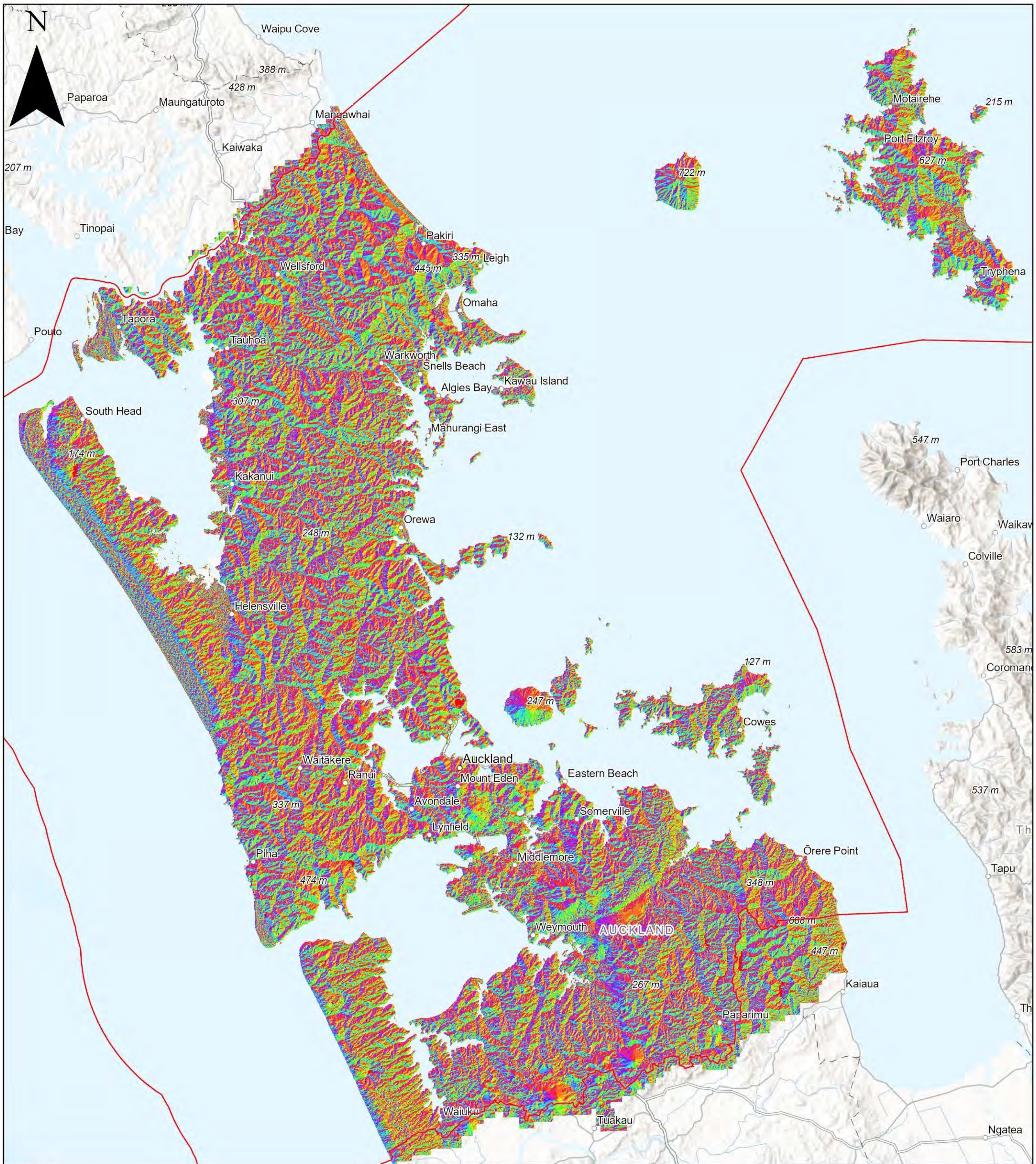

Figure:

Aspect Raster of the Auckland Region

Legend

Auckland Region

Aspect

360

-1

Prepared For:

Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by:

wsp

Date:
25/06/2024

Sheet:
1 of 1

Notes:
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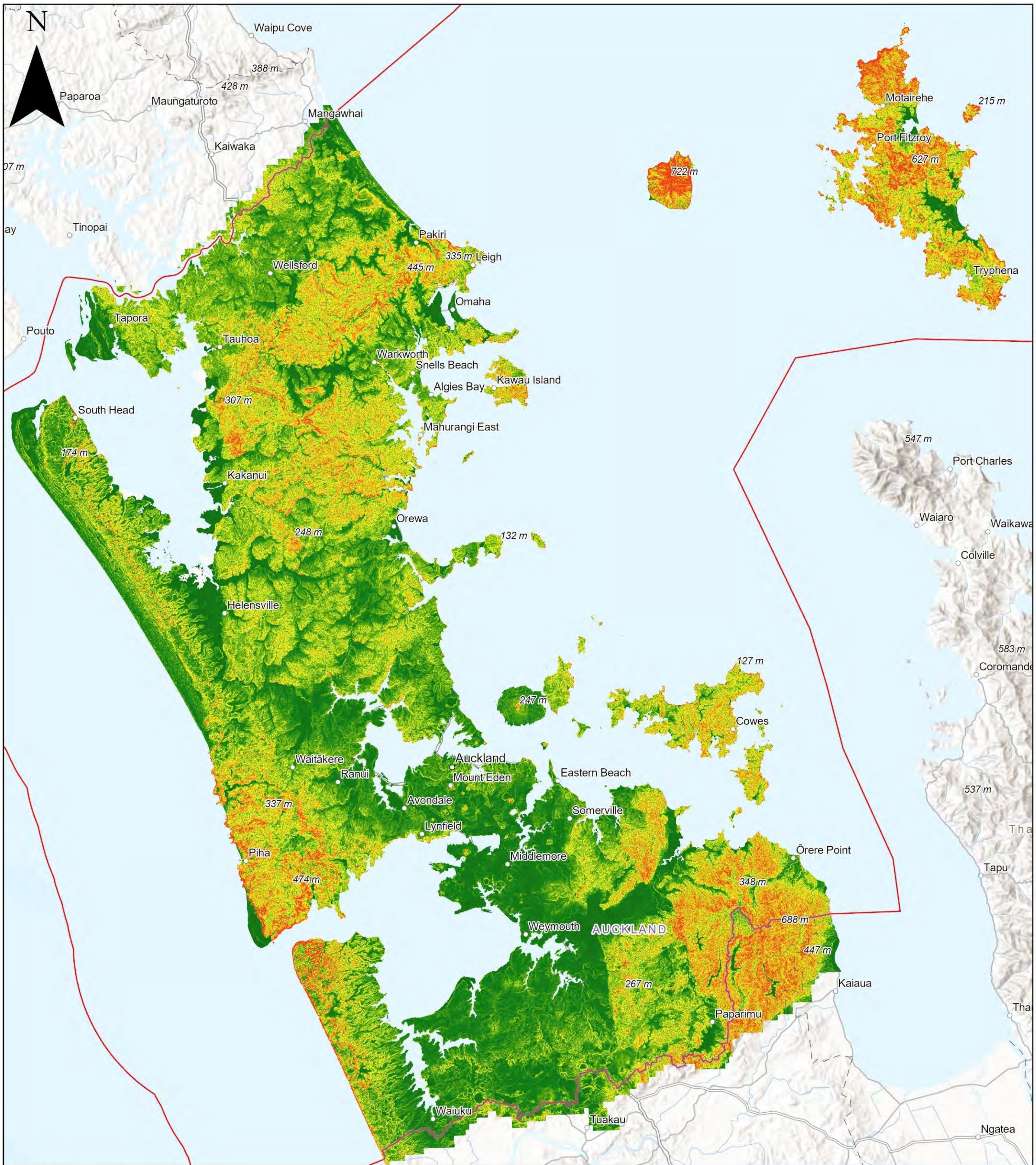

Figure:

Slope Raster of the Auckland Region

Legend:

Auckland Region

Slope

80

0

0 5 10 20 Kilometers

Prepared For:

Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by:

wsp

Date:

25/06/2024

Sheet:

1 of 1

Notes:

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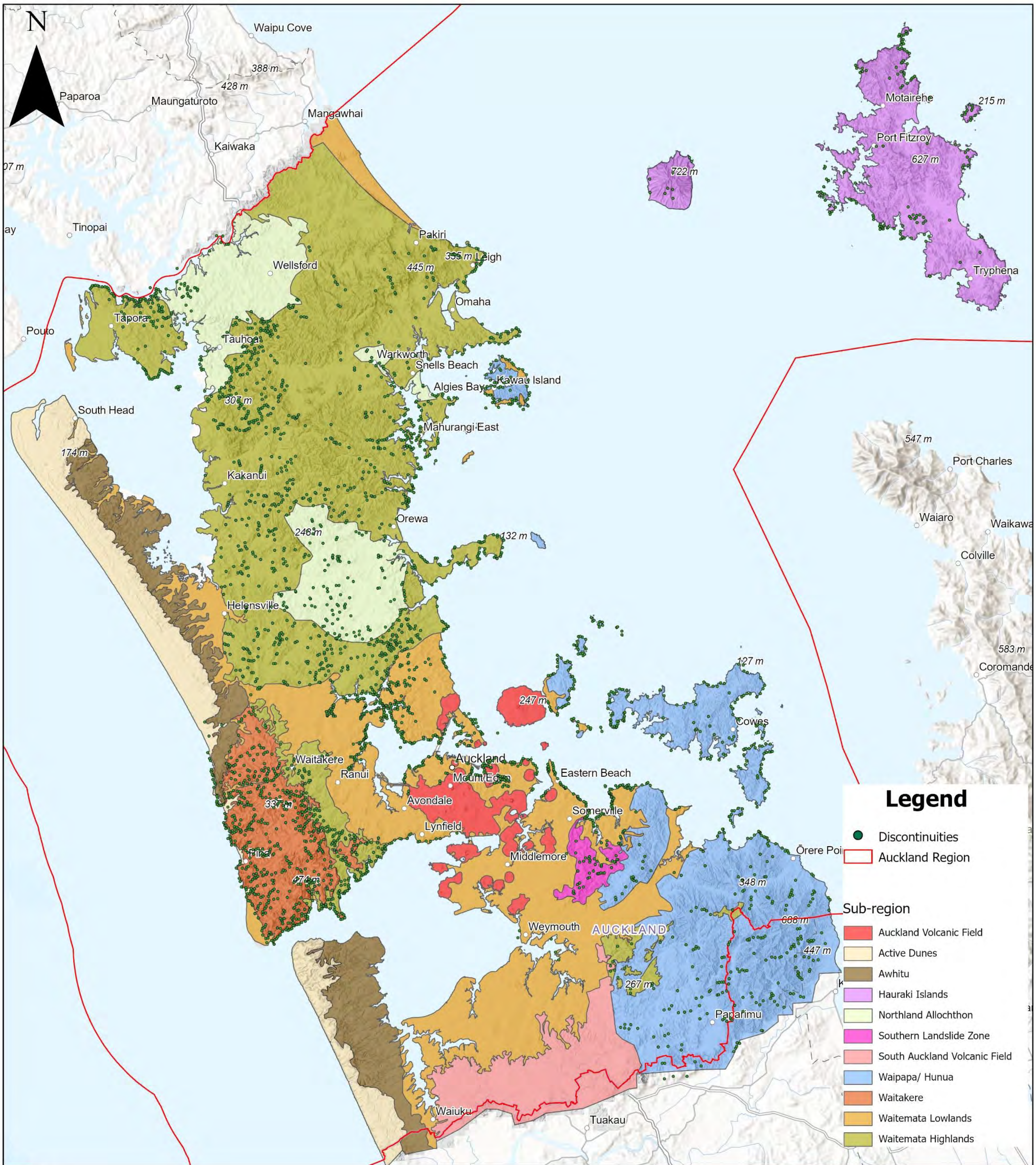

Figure:

Sub-regions and discontinuities of the Auckland Region

0 5 10 20
Kilometers

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Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by: wsp

Date: 25/06/2024

Sheet: 1 of 1

Notes:

This map is intended to be viewed with the Auckland Landslide Study Technical Report. This study is a region-wide assessment and does not account for property-specific ground conditions.

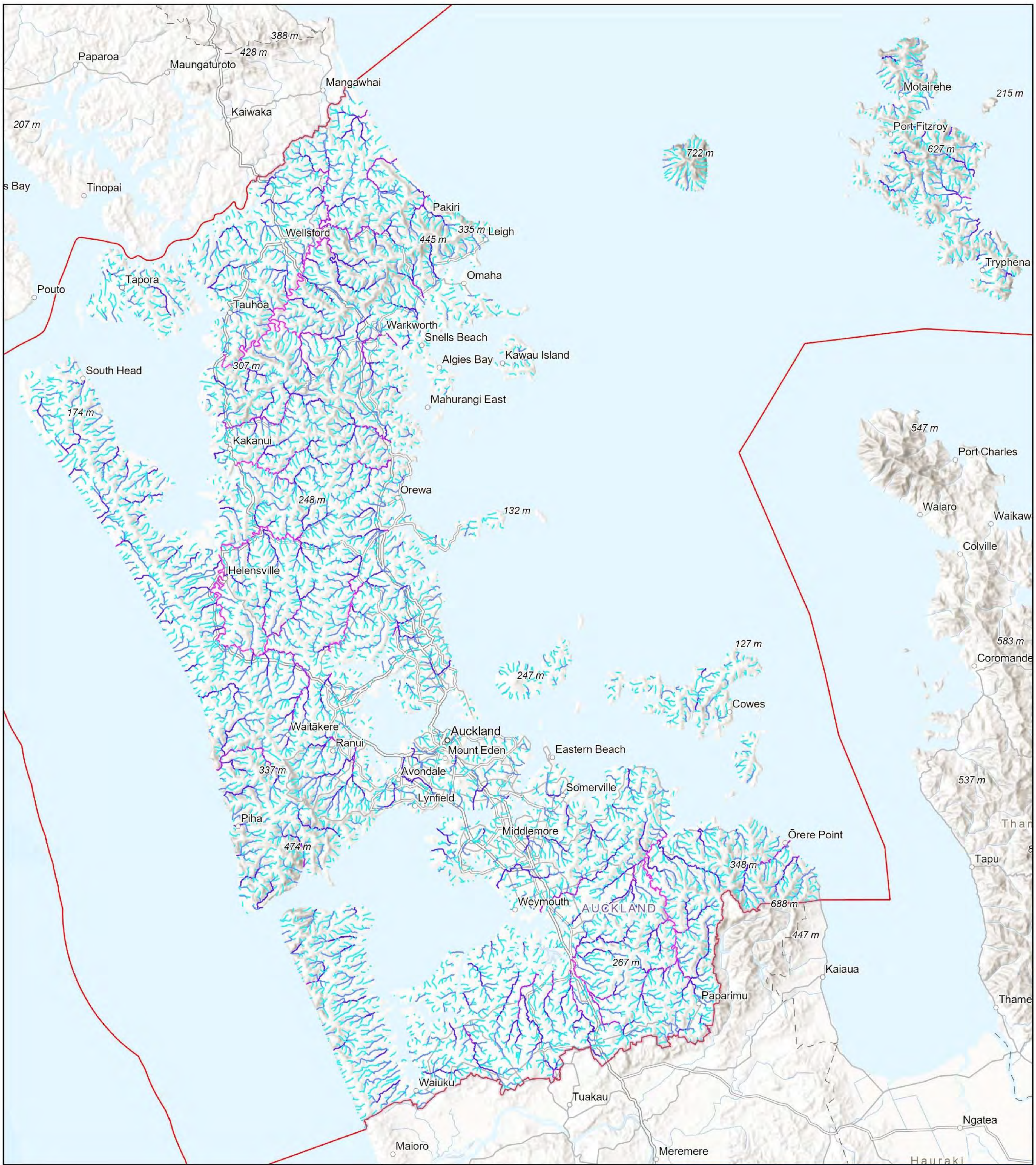

Figure:

REC2 stream order map of the Auckland Region

Prepared For:

Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by: wsp

Date: 25/06/2024

Sheet: 1 of 1

Legend

Auckland

REC2 stream lines

Stream Order

- 1
- 2
- 3
- 4
- 5 - 6

Notes:
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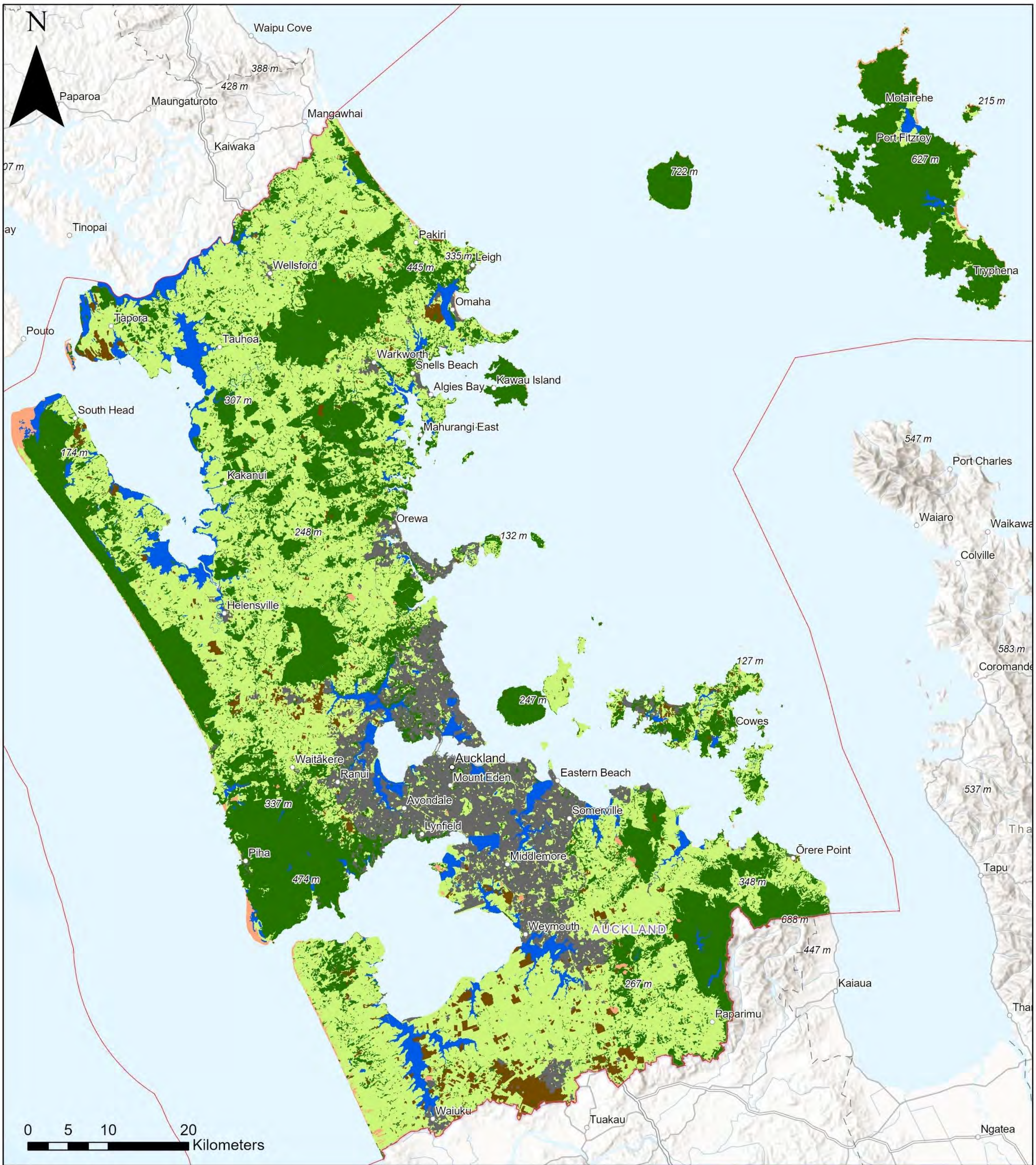

Figure:

Land Cover (2018) of the Auckland Region

Legend:

Auckland Region

Forest
Water Bodies
Bare
Grassland
Scrub/shrubland
Artificial Areas

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Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by: wsp

Date: 25/06/2024

Sheet: 1 of 1

Notes:
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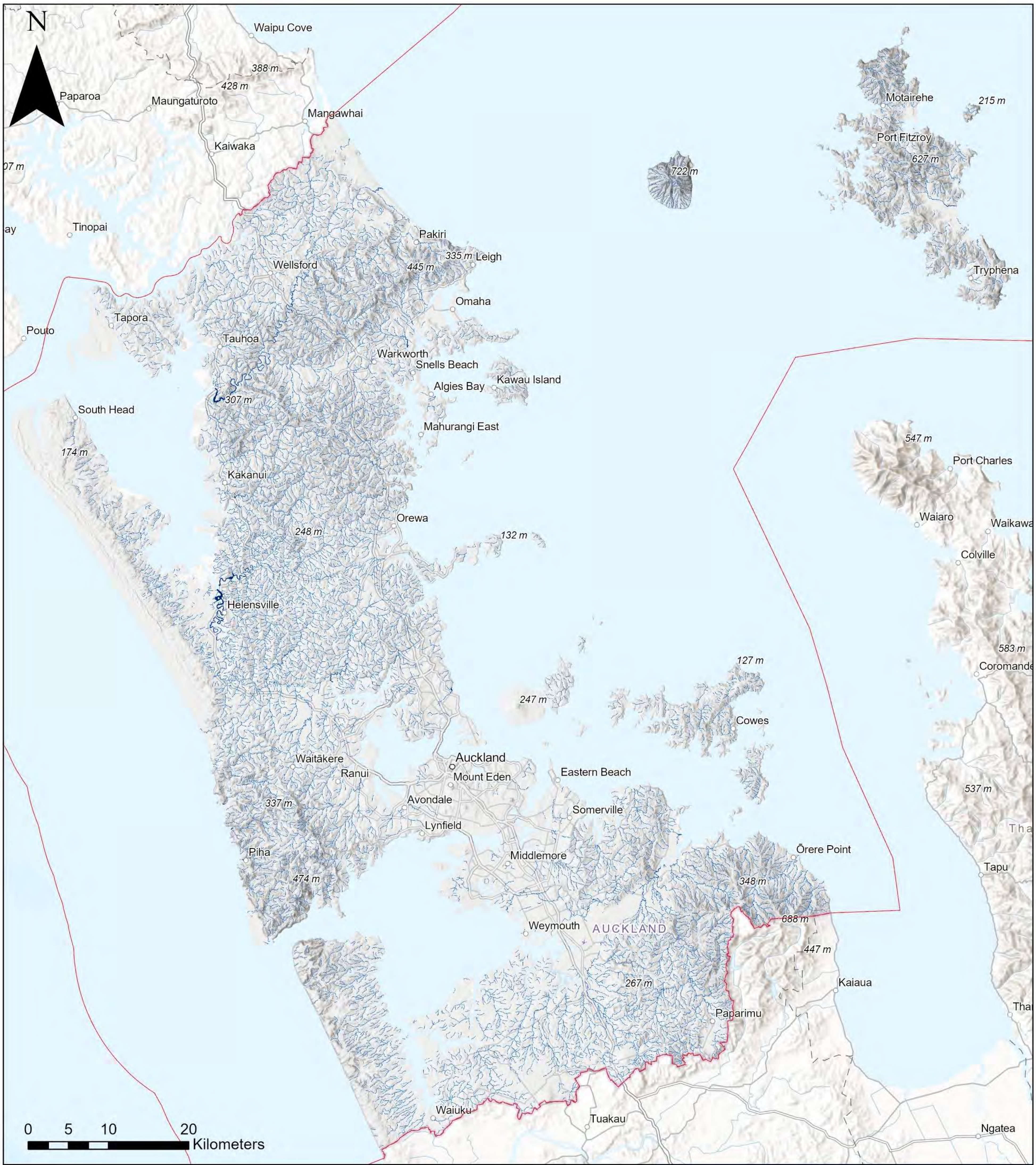

Figure:

Distance to Stream Raster

Legend:

Auckland Region

Distance to Stream

5

10

20

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Project code: 1-C1875.24

Prepared by: wsp

Date: 25/06/2024

Sheet: 1 of 1

Notes:
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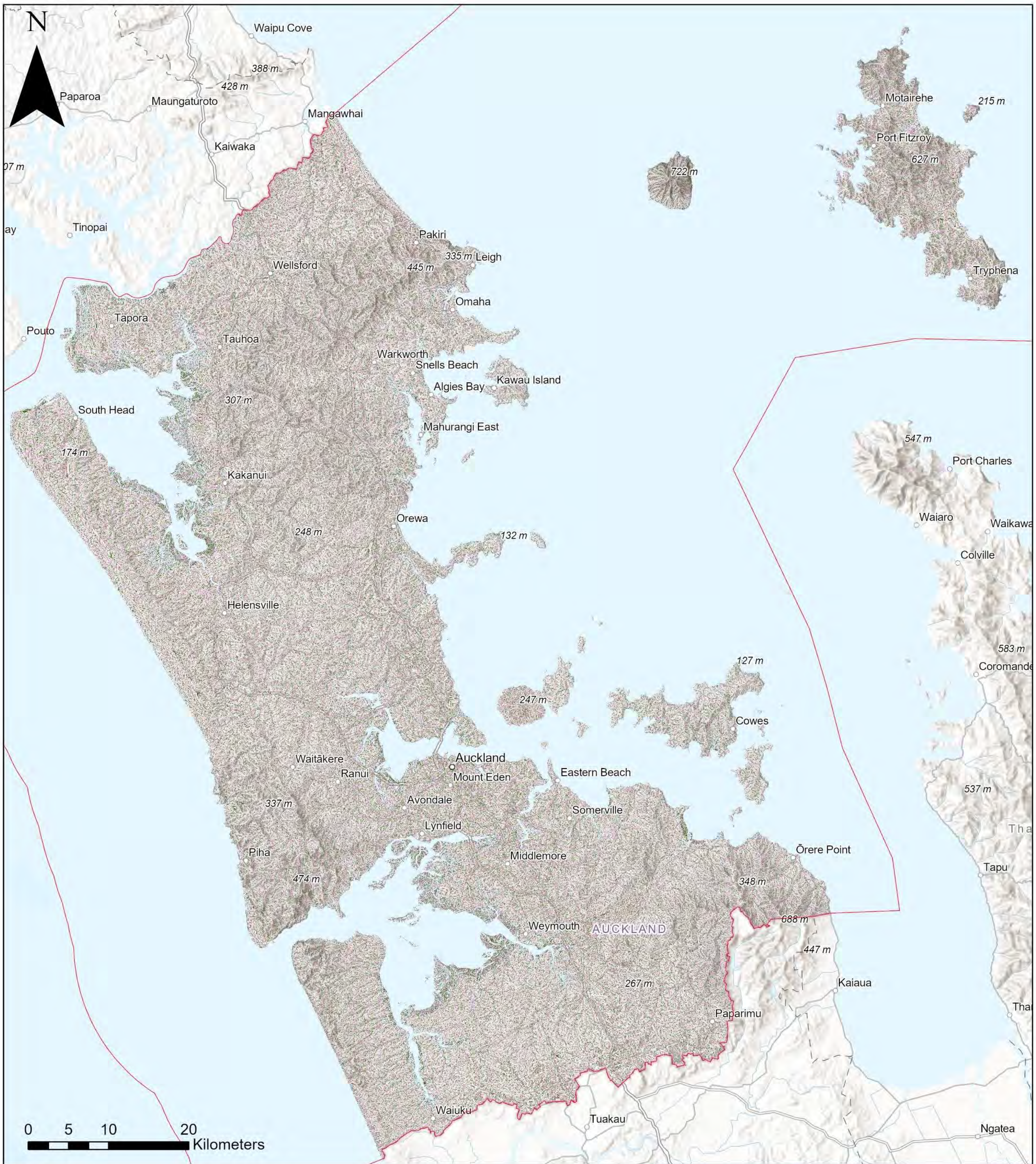

Figure:

Distance to Overflow Land Flow Path

Prepared For:

Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by:

Date: 25/06/2024

Sheet: 1 of 1

Legend:

Auckland Region

Distance to Overflow Land Flow Path

5

10

Notes:

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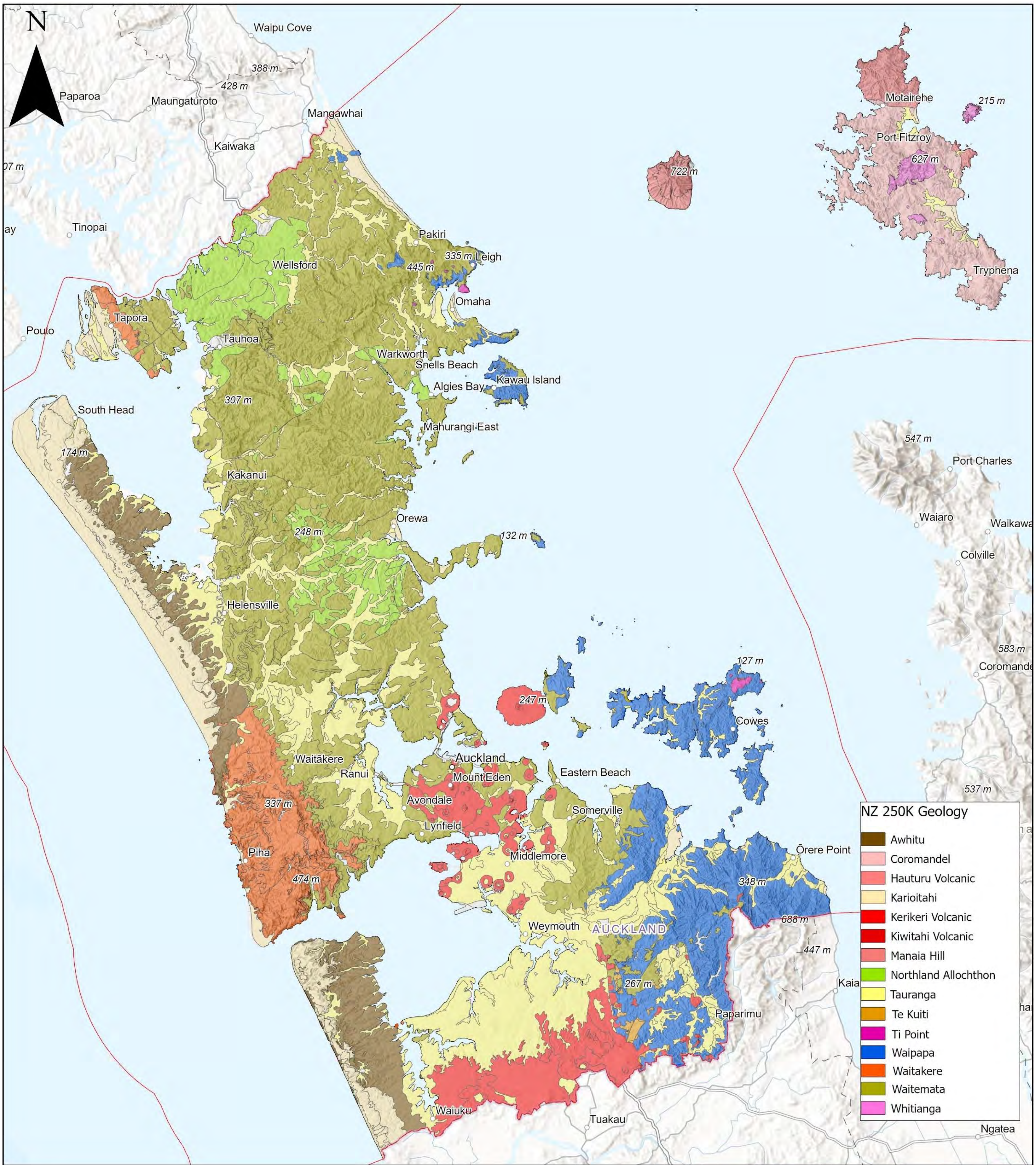


Figure:

Geology Map of the Auckland Region

Legend:

Auckland Region

0 5 10 20 Kilometers

Prepared For:

Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by:

Date: 25/06/2024

Sheet: 1 of 1

Notes:

This map is intended to be viewed with the Auckland Landslide Study Technical Report. This study is a region-wide assessment and does not account for property-specific ground conditions.

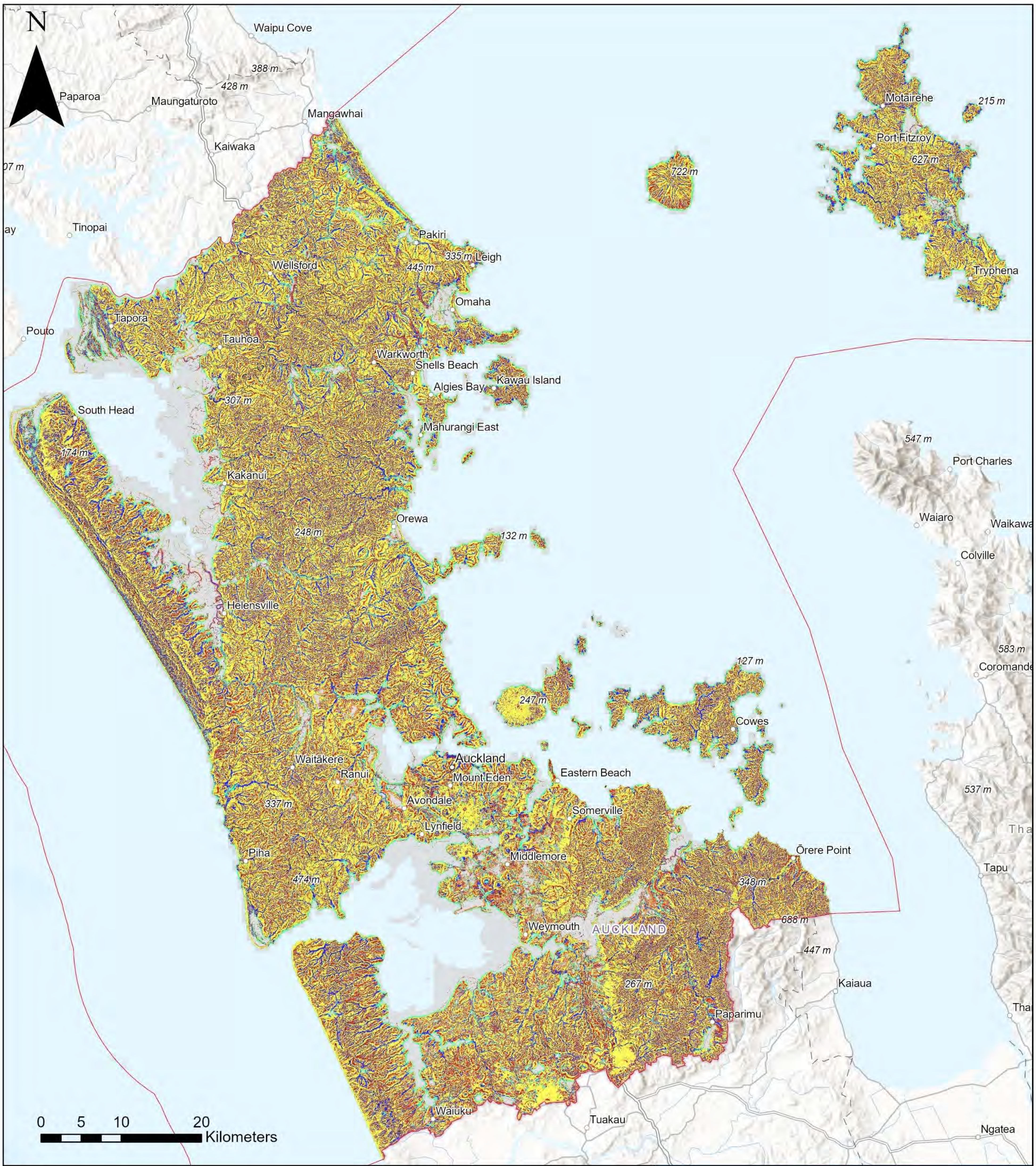


Figure:

Geomorphons of the Auckland Region

Prepared For:

Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by: WSP

Date: 25/06/2024

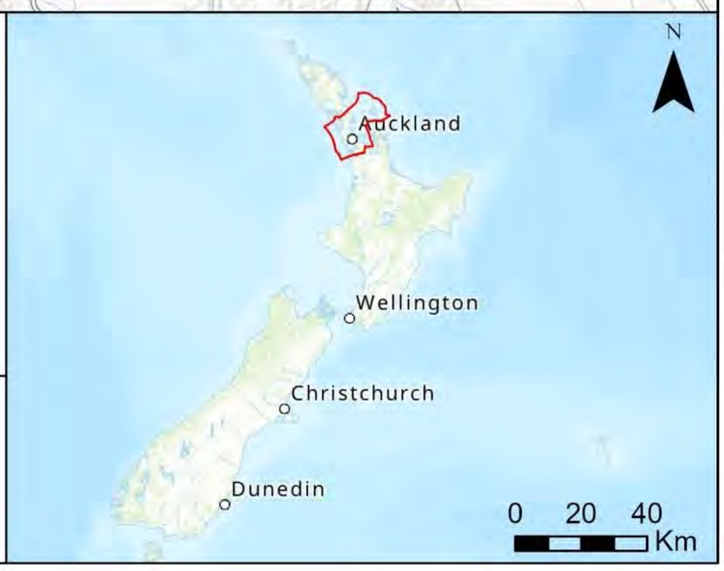
Sheet: 1 of 1

Legend:

Auckland Region

Geomorphon 32 m

Flat	Slope
Peak	Hollow
Ridge	Foot slope
Shoulder	Valley
Spur	Pit



Notes:

This map is intended to be viewed with the Auckland Landslide Study Technical Report. This study is a region-wide assessment and does not account for property-specific ground conditions.

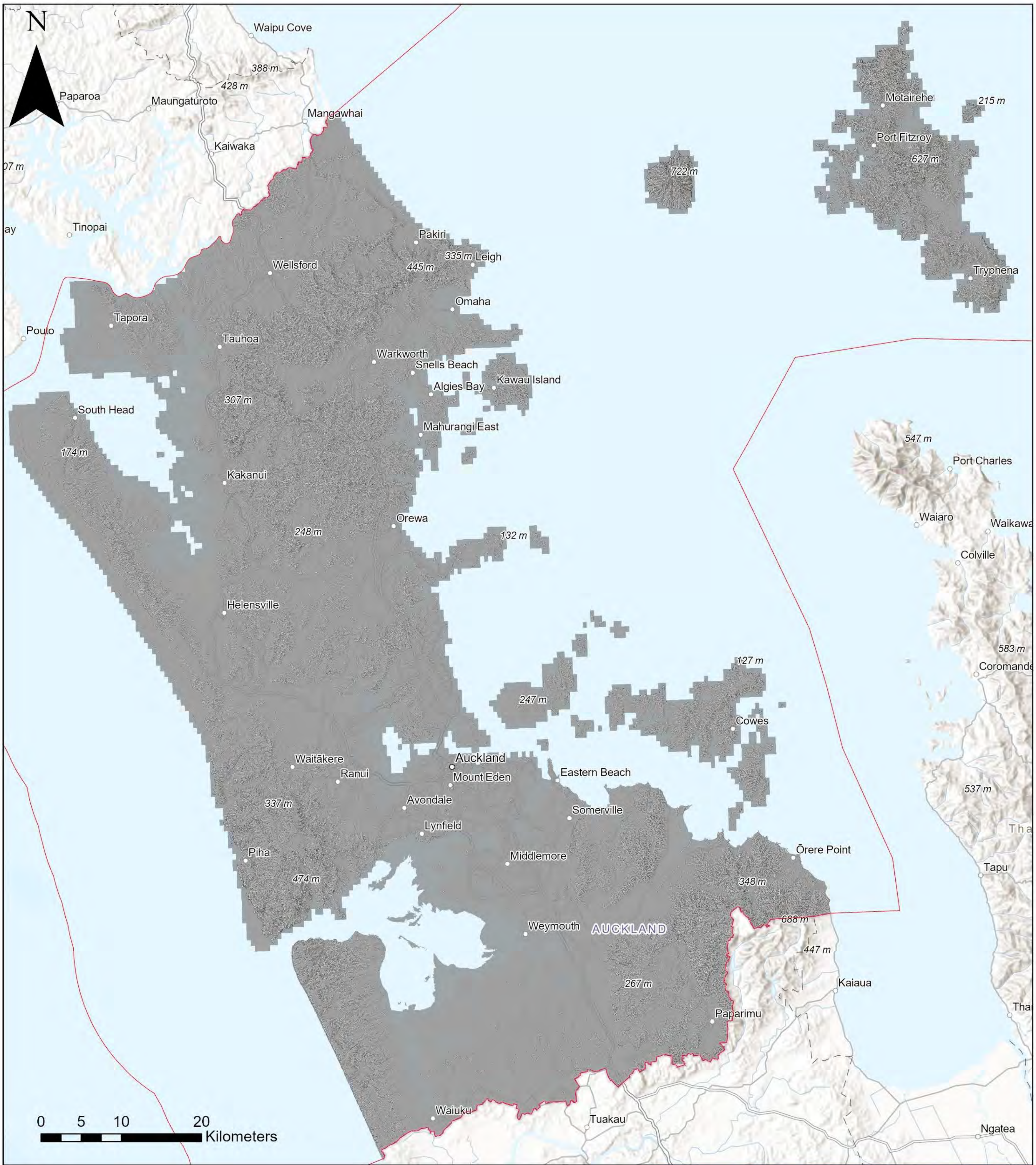


Figure:

Curvature Raster of the Auckland Region

Legend:

Auckland Region

Curvature 32 m

30.2361

-40.3629

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Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by:	**Date:**	**Sheet:**	**Notes:**
wsp	25/06/2024	1 of 1	This map is intended to be viewed with the Auckland Landslide Study Technical Report. This study is a region-wide assessment and does not account for property-specific ground conditions.

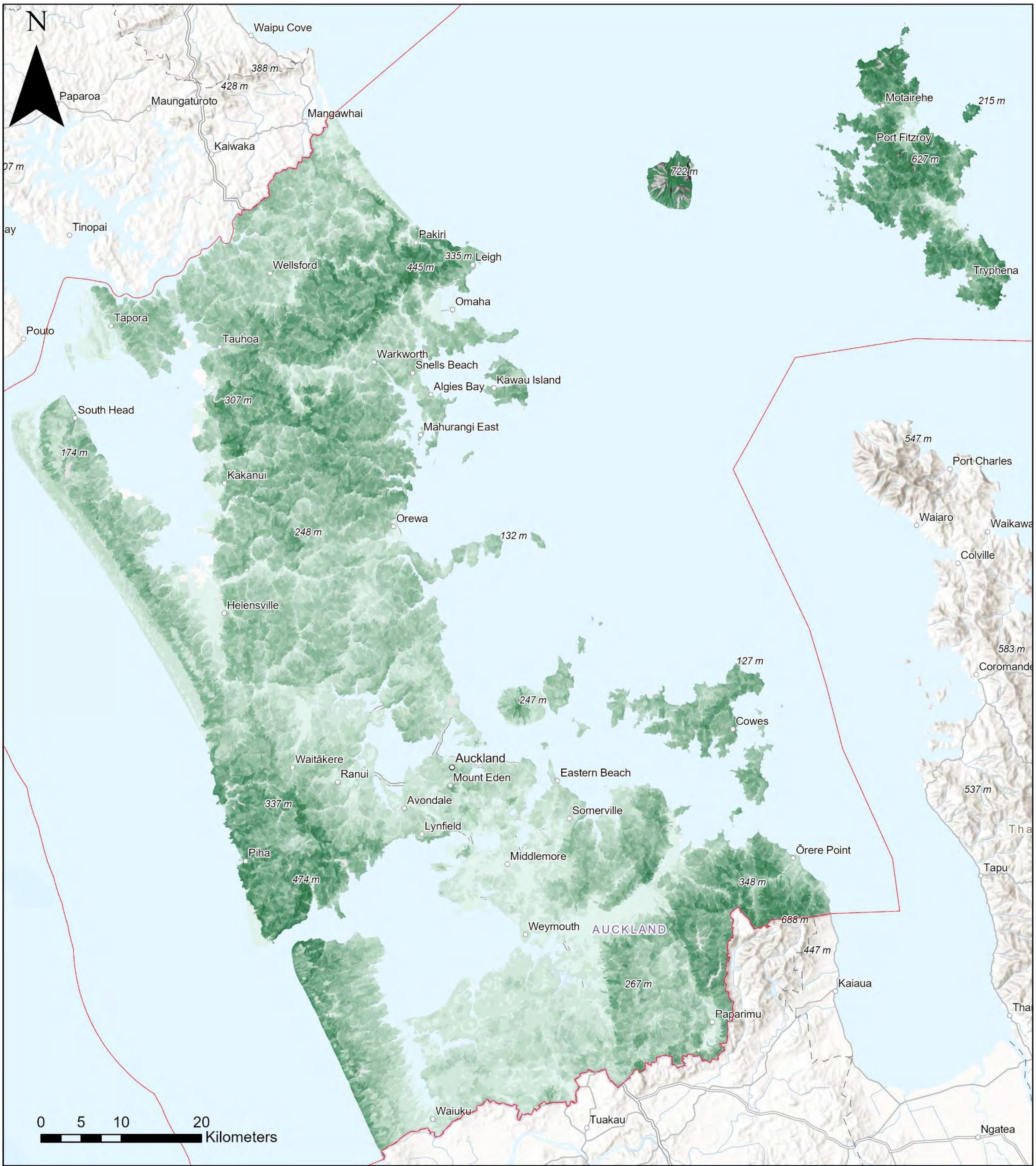


Figure:

Relief Raster of the Auckland Region

Legend:

Auckland Region

Relief (m)

0.0

360

Prepared For:

Auckland Council.
Auckland Landslide Study.
Project code: 1-C1875.24

Prepared by:

Date: 25/06/2024

Sheet: 1 of 1

Notes:
This map is intended to be viewed with the Auckland Landslide Study Technical Report. This study is a region-wide assessment and does not account for property-specific ground conditions.

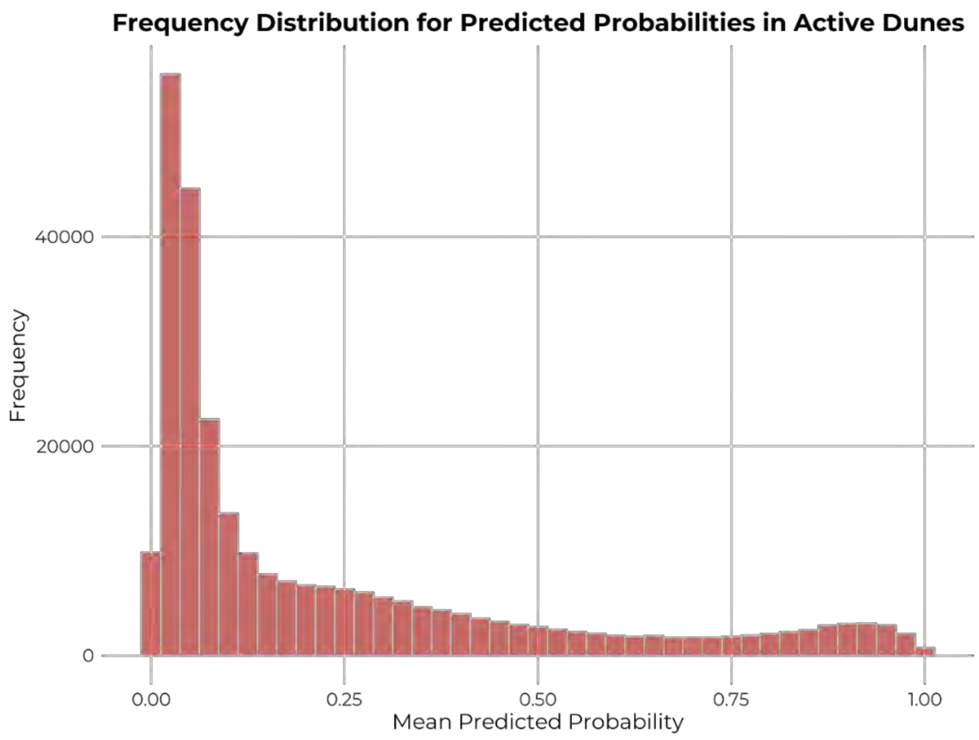
APPENDIX C – SHALLOW LANDSLIDE SUSCEPTIBILITY MODEL OUTPUTS

ACTIVE DUNES

MODEL COEFFICIENTS

Variable	Mean Coefficient	Standard Error	95% Confidence Interval	
			Upper Bound	Lower Bound
Intercept	-19.1511	0.127263	-18.9016	-19.4006
Aspect	-0.05529	0.001255	-0.05283	-0.05775
Curvature	-0.07556	0.001201	-0.0732	-0.07791
GeolUnit4	-1.81286	0.002096	-1.80875	-1.81697
GeolUnit9	2.068143	0.024852	2.116864	2.019422
Geomorphon2	12.11116	0.020184	12.15074	12.07158
Geomorphon3	12.76761	0.018591	12.80406	12.73115
Geomorphon4	-1.50559	0.026454	-1.45372	-1.55747
Geomorphon5	13.32523	0.018625	13.36175	13.28871
Geomorphon6	13.3156	0.018305	13.35149	13.2797
Geomorphon7	13.68832	0.018252	13.72411	13.65253
Geomorphon8	8.318206	0.144207	8.600992	8.035419
Geomorphon9	14.16393	0.0181	14.19942	14.12844
Geomorphon10	14.53769	0.019545	14.57602	14.49936
DistanceToStream10	-1.44034	0.253026	-0.94396	-1.93673
DistanceToStream20	-3.77139	0.195297	-3.38826	-4.15452
DistanceToStream9999	-5.13056	0.175484	-4.7863	-5.47482
LCDB1	14.94004	0.030553	14.99994	14.88014
LCDB2	21.78952	0.104959	21.99529	21.58375
LCDB3	15.54807	0.032628	15.61204	15.4841
LCDB4	15.40633	0.030537	15.4662	15.34647
LCDB5	14.47937	0.030727	14.53961	14.41913
LCDB7	10.6948	0.096184	10.88336	10.50623
Local Slope Relief	0.46543	0.001488	0.468348	0.462512
Slope	0.974801	0.001	0.976761	0.972842
OLFP10	-0.18652	0.005175	-0.17638	-0.19667
OLFP9999	-0.34032	0.003931	-0.33261	-0.34802

PROBABILITY DISTRIBUTION



AREA COMPARISONS

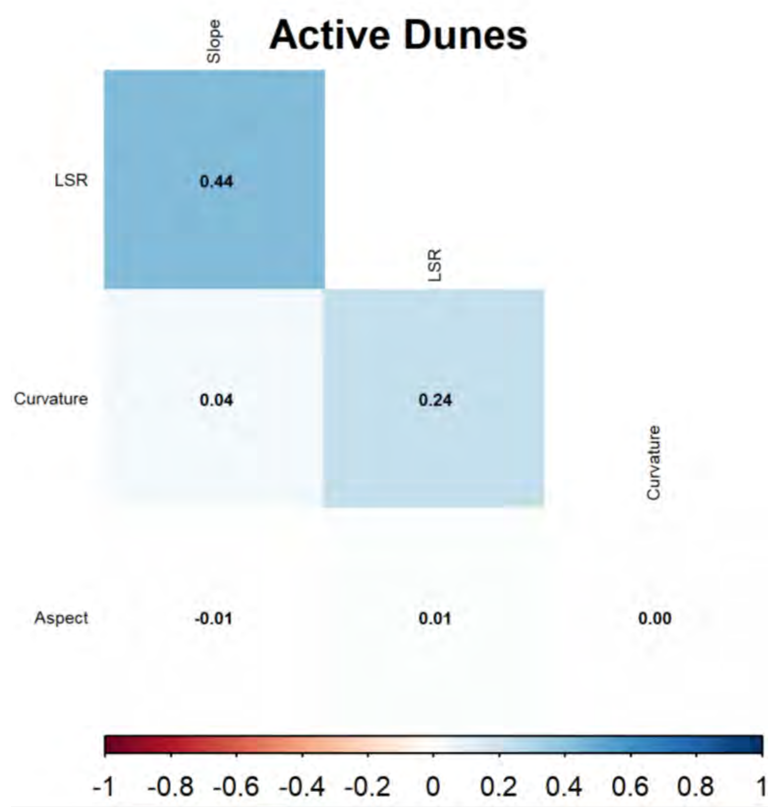
	Land area comparison					
	Active Dunes					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	43.9%	38.6%	75.0%	71.8%	62.7%	60.0%
Low	36.0%	38.5%	6.2%	6.8%	21.2%	21.6%
Moderate	15.4%	17.2%	6.3%	7.3%	4.8%	5.7%
High	4.7%	5.7%	6.3%	6.8%	4.6%	4.9%
Very High			6.3%	7.3%	6.7%	7.8%

	Landslide inventory density (landslide area per class/total landslide area per region)					
	Active Dunes					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	1.1%	0.8%	7.3%	5.0%	2.9%	2.4%
Low	8.9%	6.9%	3.3%	3.7%	10.7%	7.5%
Moderate	40.0%	31.3%	7.6%	5.5%	6.9%	6.3%
High	50.0%	61.1%	21.1%	17.7%	15.4%	13.8%
Very High			60.8%	68.2%	64.1%	70.0%

	Landslide number density (landslide cells/total cells per region)					
	Active Dunes					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Low	0.1%	0.1%	0.2%	0.2%	0.2%	0.1%
Moderate	0.9%	0.7%	0.4%	0.3%	0.5%	0.4%
High	3.8%	3.8%	1.2%	0.9%	1.2%	1.0%
Very High			3.5%	3.3%	3.4%	3.2%

VARIABLE CORRELATIONS

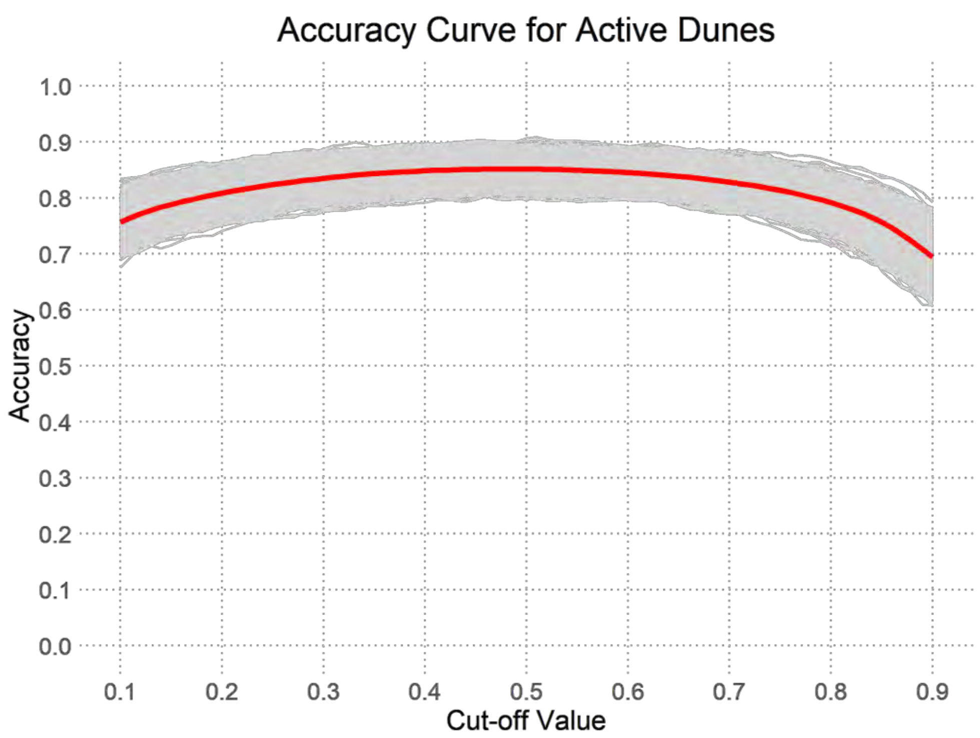
Continuous Variables



Categorical Variables

GeolUnit_vs_Geomorphon	0.104629618
GeolUnit_vs_DistanceToStream	0.080565886
GeolUnit_vs_LCDB	0.352265784
GeolUnit_vs_OLFP	0.033361073
Geomorphon_vs_DistanceToStream	0.099831060
Geomorphon_vs_LCDB	0.180921188
Geomorphon_vs_OLFP	0.188155982
DistanceToStream_vs_LCDB	0.042168461
DistanceToStream_vs_OLFP	0.057906110
LCDB_vs_OLFP	0.037570667

ACCURACY PLOT



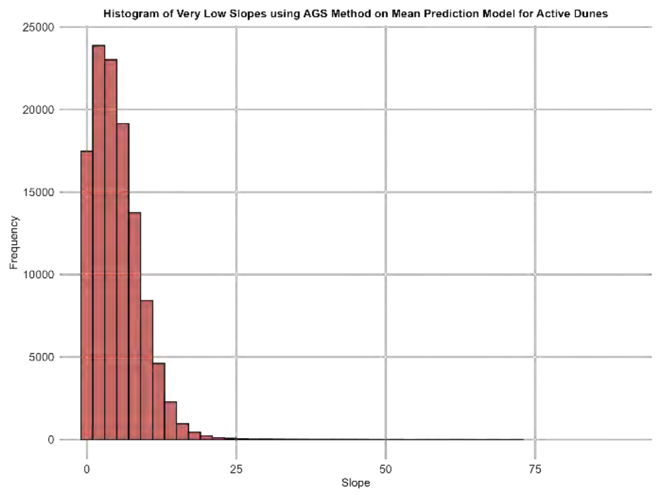
SLOPE ANGLE DISTRIBUTIONS

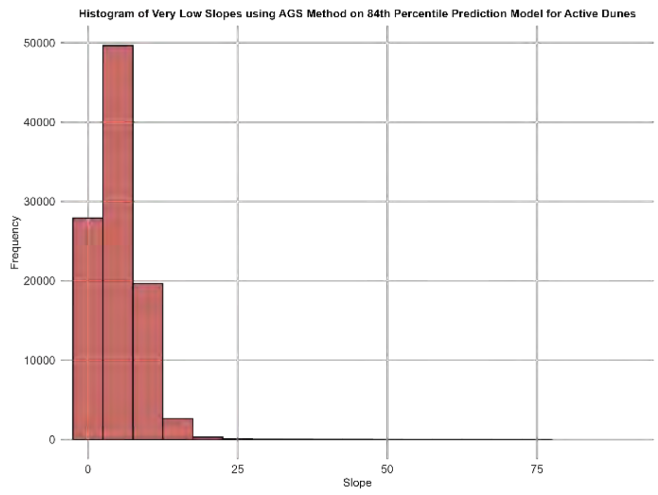
METHOD 1 (AGS)

Mean predictions

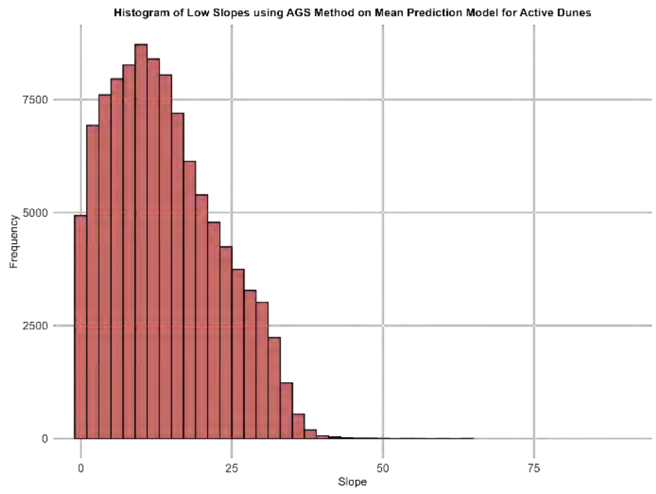
84th percentile predictions

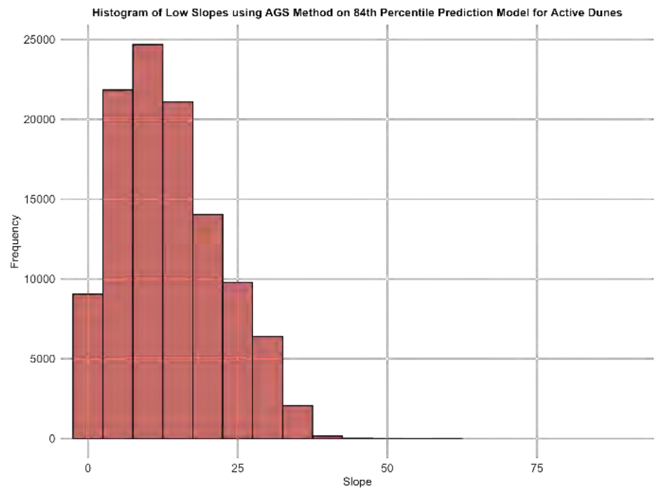
Very Low



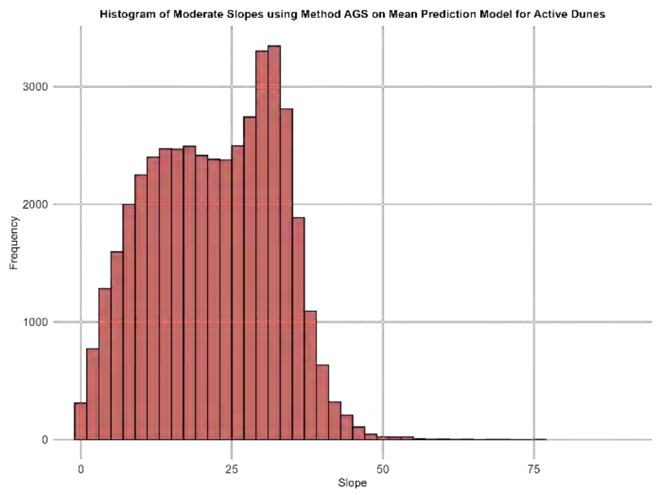


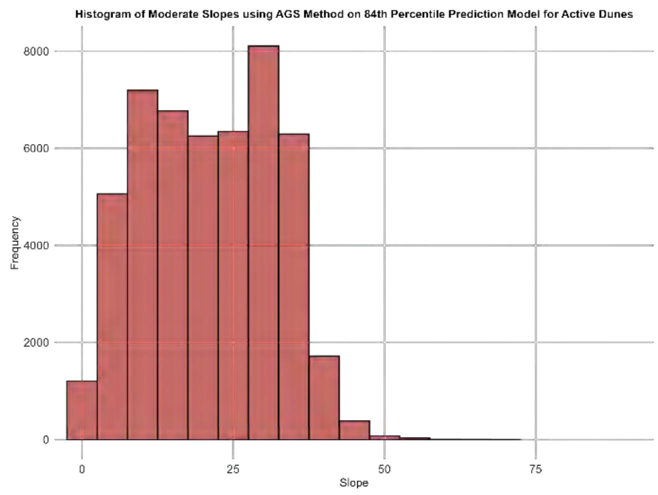
Low



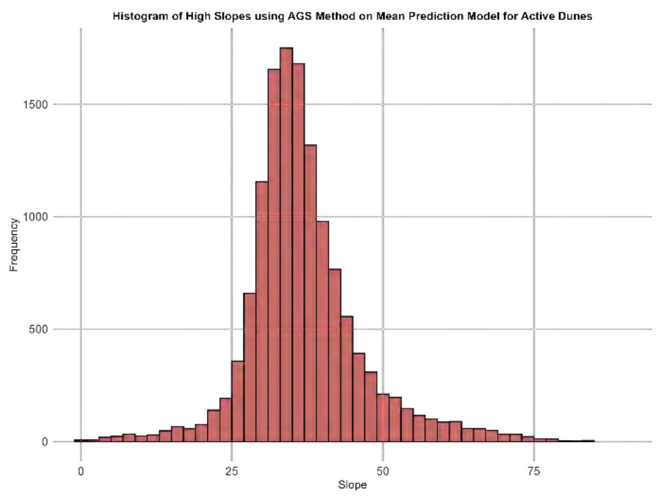


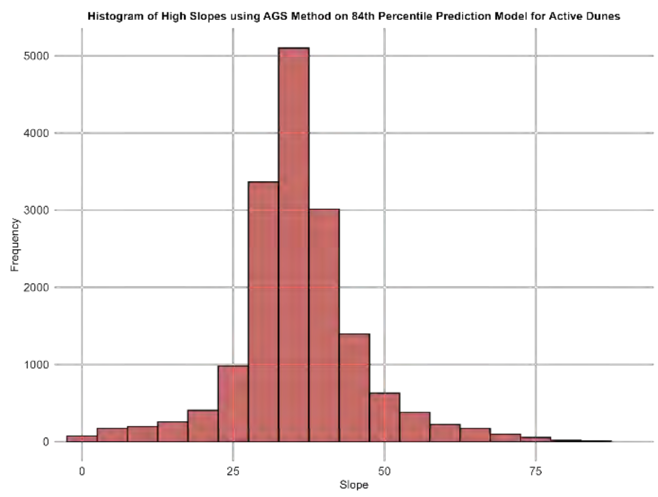
Moderate





High

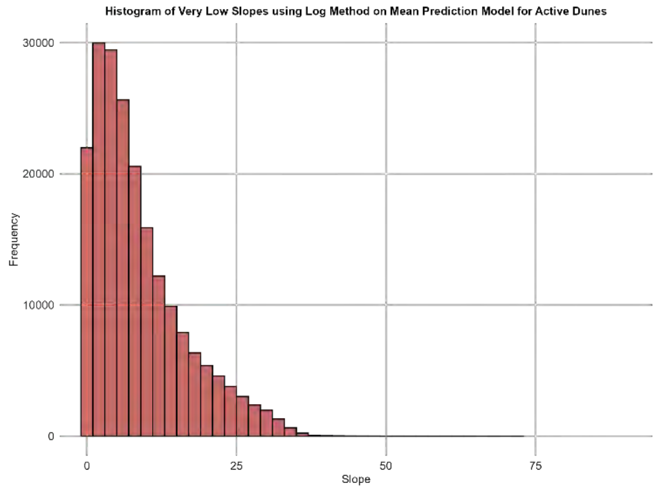


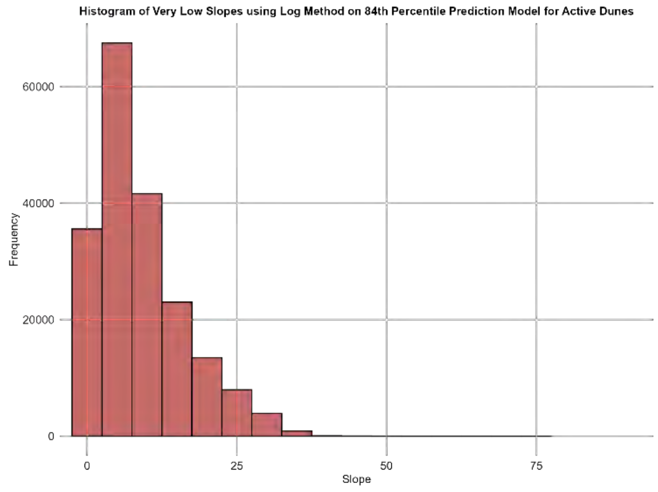


METHOD 2 (LOG BINS)

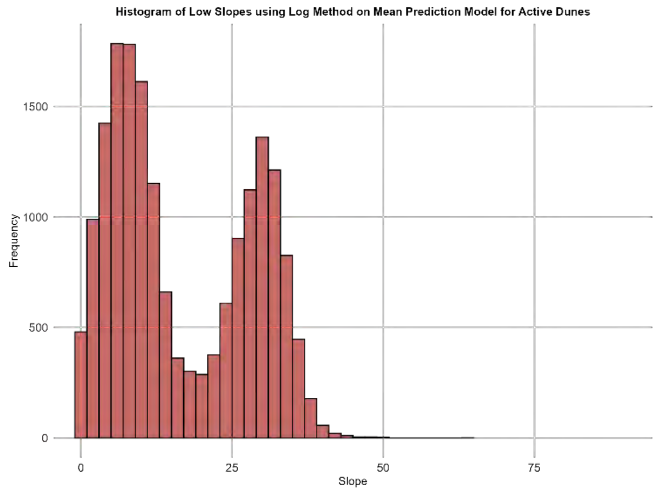
Mean predictions | 84th percentile predictions

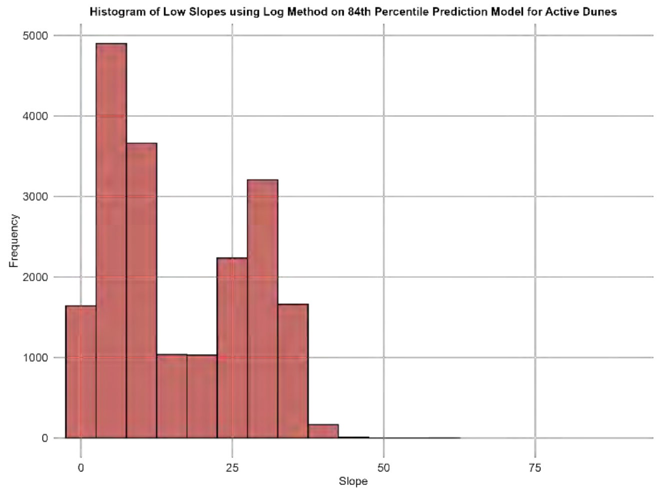
Very Low



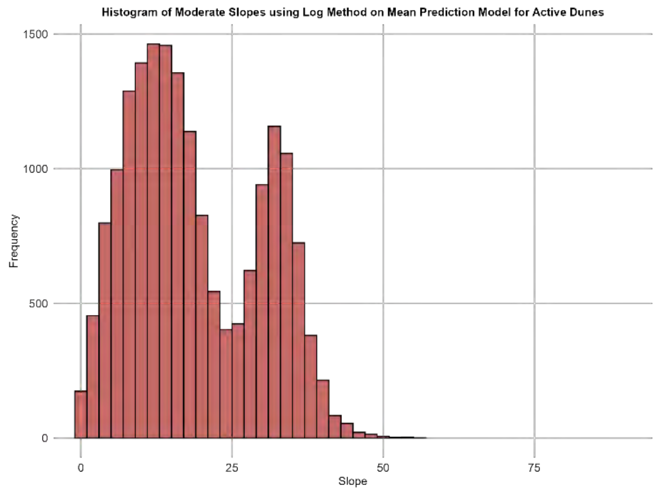


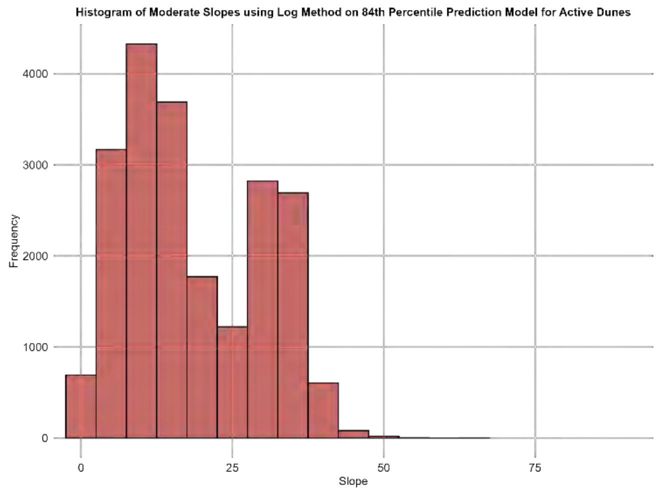
Low





Moderate





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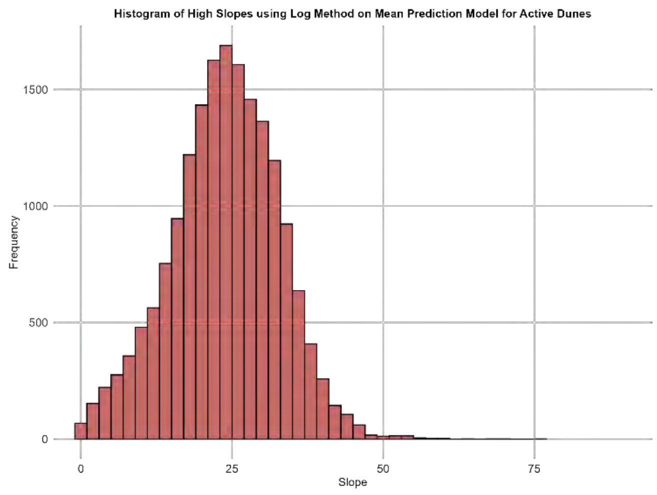
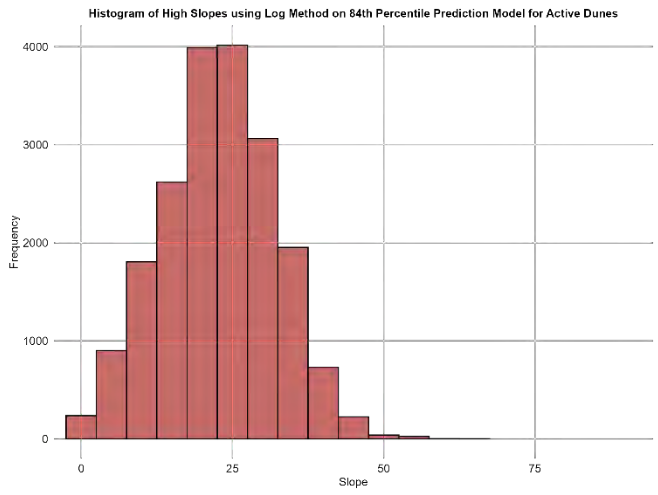
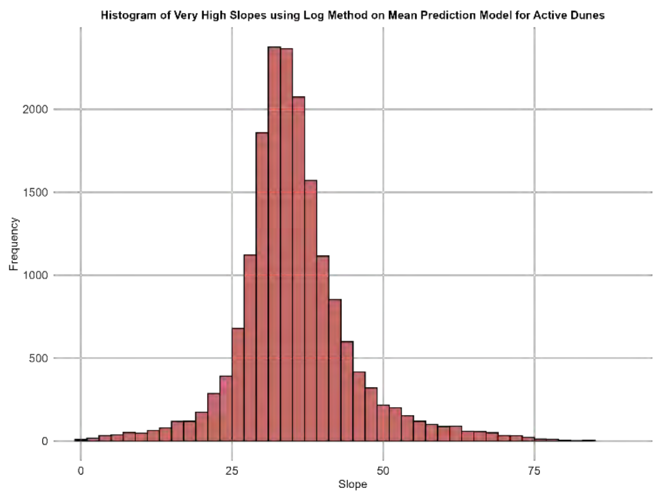
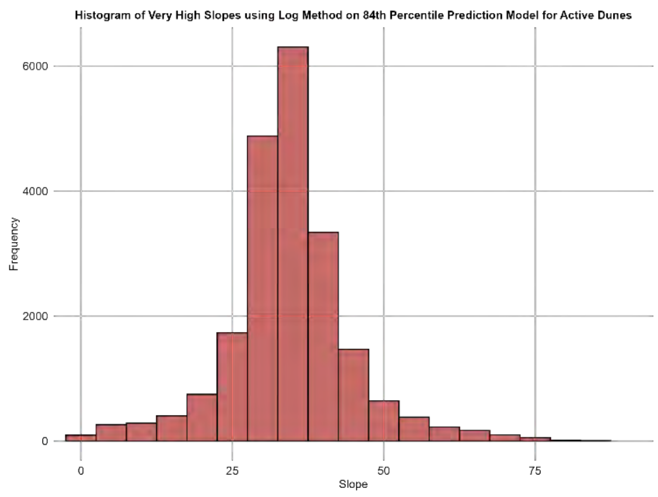




Very High



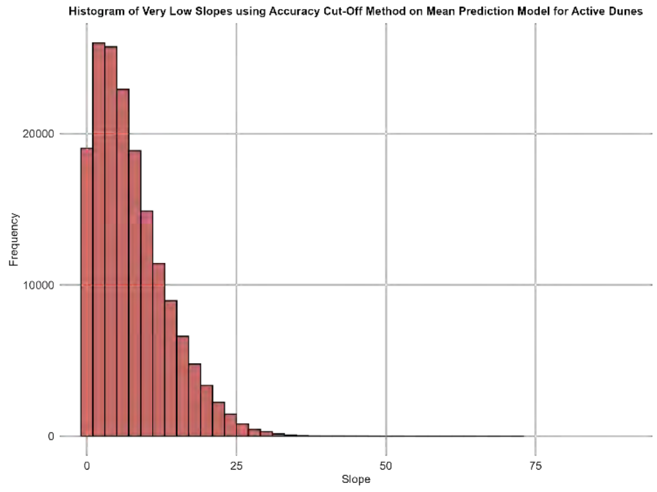


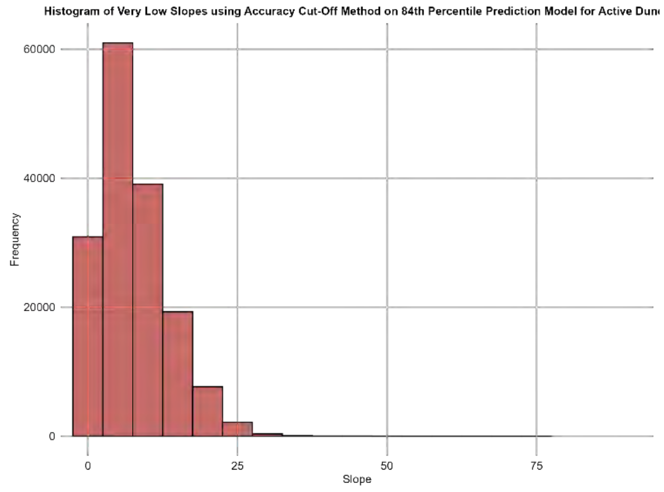
METHOD 3 (ACCURACY CUT-OFF)

Mean predictions

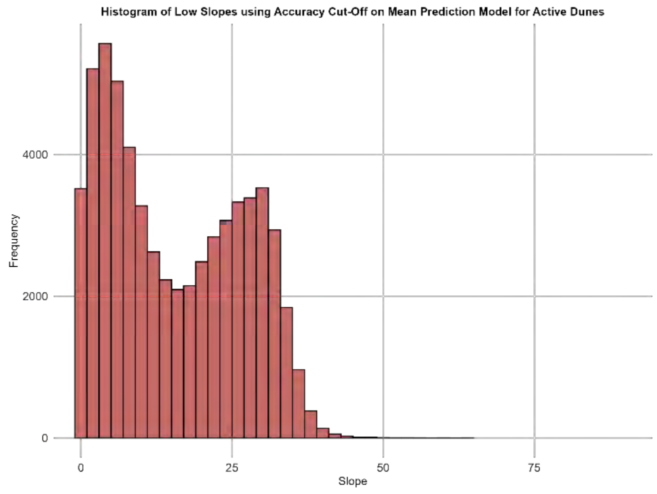
84th percentile predictions

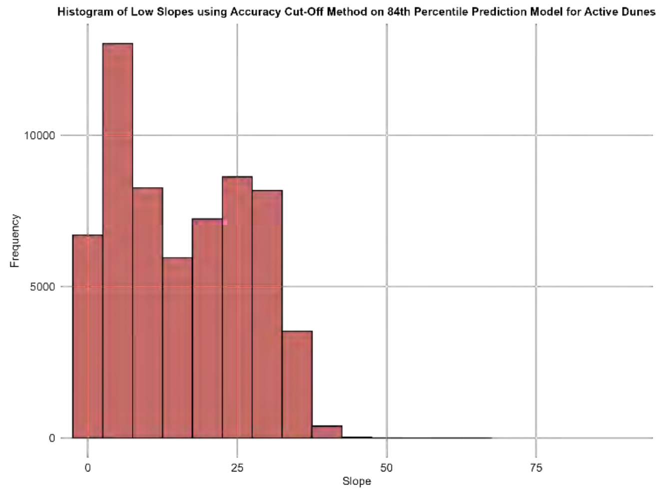
Very Low



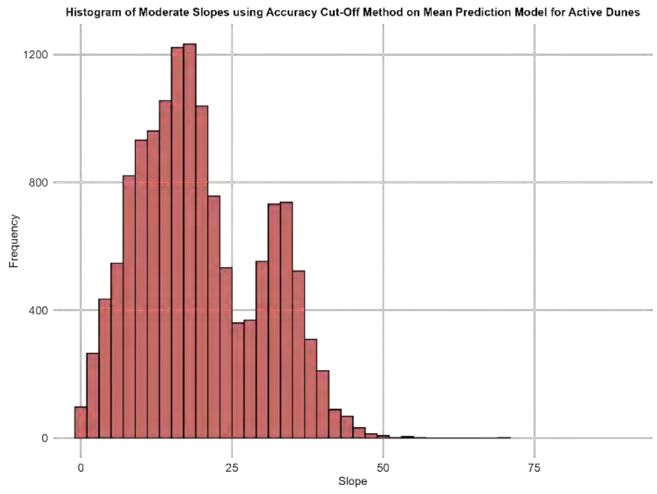


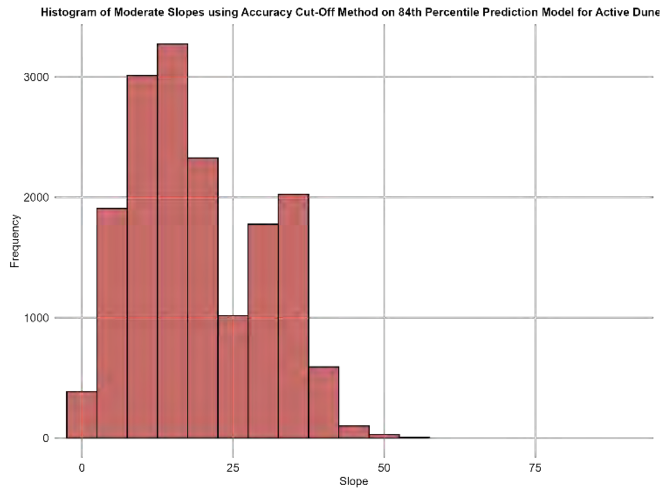
Low





Moderate





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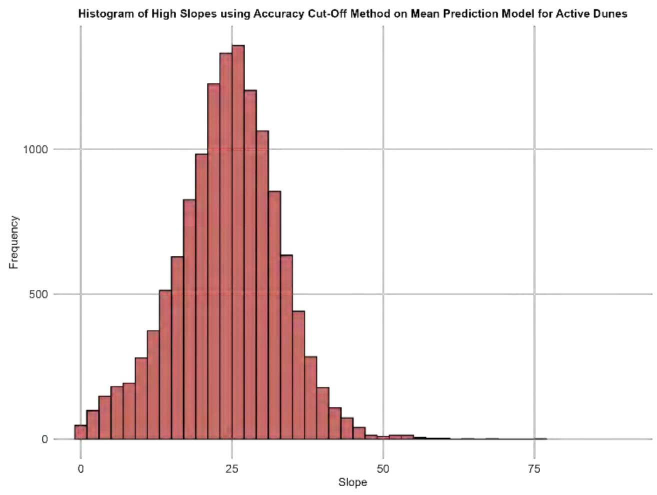
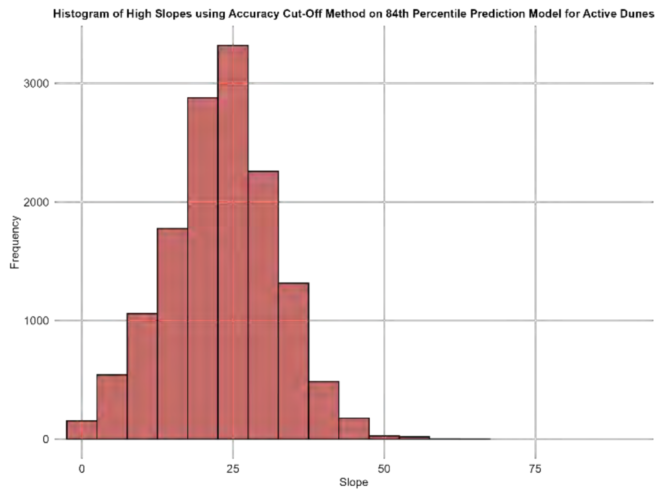
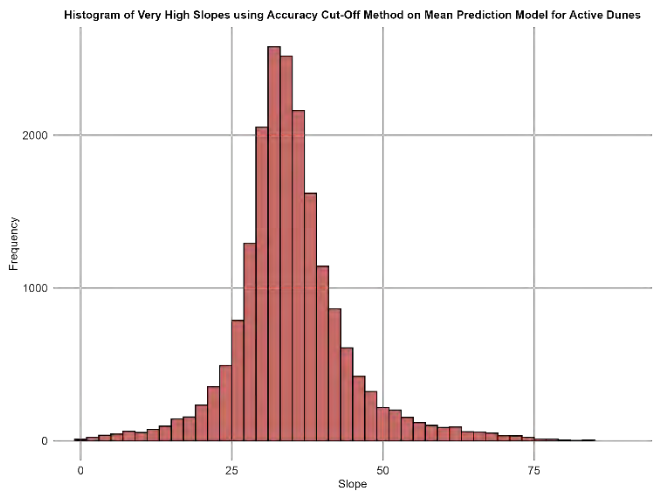
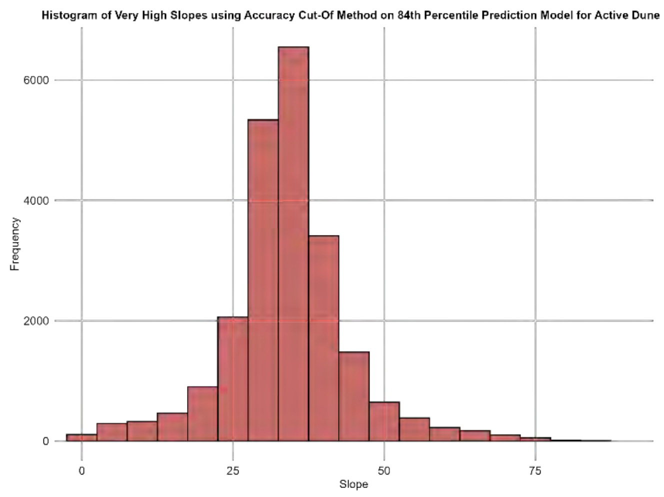




Very High



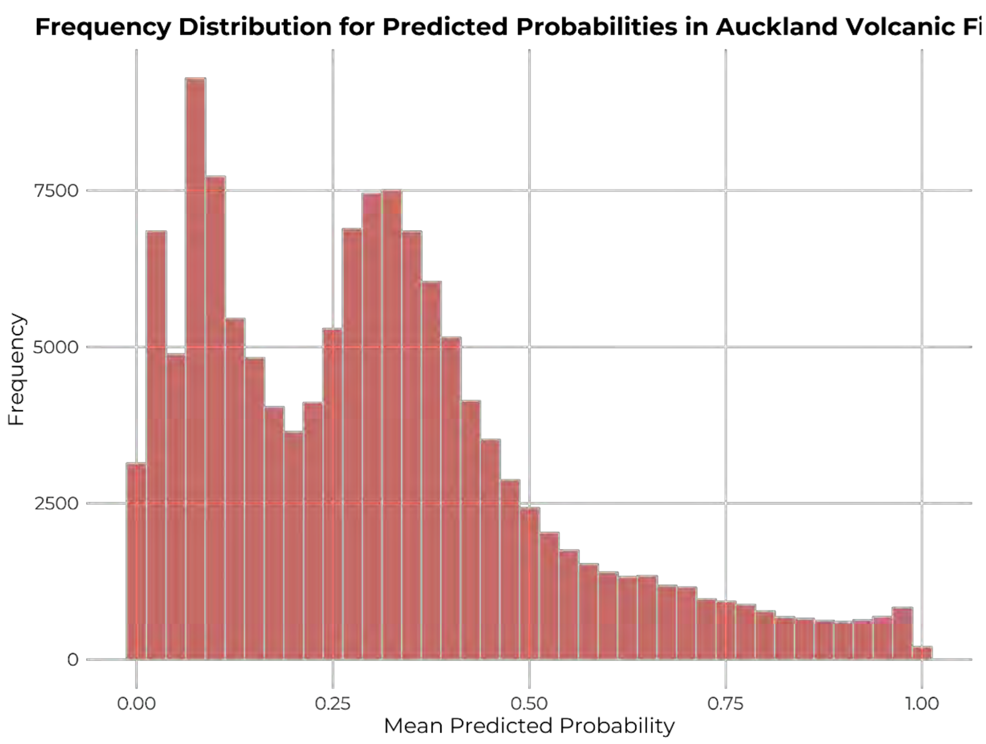


AUCKLAND VOLCANIC FIELD

MODEL COEFFICIENTS

Variable	Mean Coefficient	Standard Error	95% Confidence Interval	
			Upper Bound	Lower Bound
Intercept	-2.00479	0.011884	-1.9815	-2.02809
Aspect	-0.08103	0.000568	-0.07992	-0.08215
Curvature	0.030015	0.000202	0.030411	0.029619
GeolUnit2	0.769624	0.006233	0.781844	0.757404
GeolUnit3	-0.5824	0.013576	-0.55579	-0.60902
GeolUnit5	0.487185	0.044868	0.575146	0.399223
GeolUnit6	-0.61172	0.002956	-0.60593	-0.61752
GeolUnit7	-11.2706	0.067923	-11.1371	-11.404
GeolUnit8	1.437925	0.0015	1.440866	1.434984
GeolUnit9	5.088473	0.097389	5.279399	4.897547
GeolUnit10	1.584915	0.004798	1.594322	1.575508
GeolUnit11	2.108924	0.007491	2.12361	2.094239
GeolUnit12	0.962965	0.002022	0.966929	0.959001
GeolUnit13	0.097753	0.002563	0.102777	0.092729
Geomorphon2	2.699047	0.010987	2.720586	2.677507
Geomorphon3	2.728284	0.010141	2.748165	2.708402
Geomorphon4	0.801572	0.010716	0.822579	0.780565
Geomorphon5	2.601163	0.01013	2.621022	2.581304
Geomorphon6	2.47147	0.010077	2.491225	2.451715
Geomorphon7	2.807301	0.010169	2.827237	2.787365
Geomorphon8	1.685743	0.01026	1.705858	1.665629
Geomorphon9	2.664735	0.010171	2.684675	2.644795
Geomorphon10	3.390841	0.010749	3.411915	3.369768
DistanceToStream10	0.469804	0.007313	0.484141	0.455466
DistanceToStream20	0.099002	0.006201	0.11116	0.086845
DistanceToStream9999	-0.41426	0.005216	-0.40404	-0.42449
LCDB1	-1.01995	0.0041	-1.01191	-1.02799
LCDB2	-1.73222	0.003795	-1.72478	-1.73966
LCDB3	-1.88402	0.004816	-1.87458	-1.89346
LCDB4	-1.49639	0.003879	-1.48879	-1.504
LCDB5	-1.03679	0.005913	-1.02519	-1.04838
LCDB7	-0.06267	0.004159	-0.05452	-0.07082
LocalSlopeRelief	0.089592	0.000658	0.090881	0.088302
Slope	0.621272	0.000529	0.622309	0.620235
OLFP10	0.103576	0.002075	0.107645	0.099508
OLFP9999	0.149922	0.001582	0.153023	0.14682

PROBABILITY DISTRIBUTION



AREA COMPARISONS

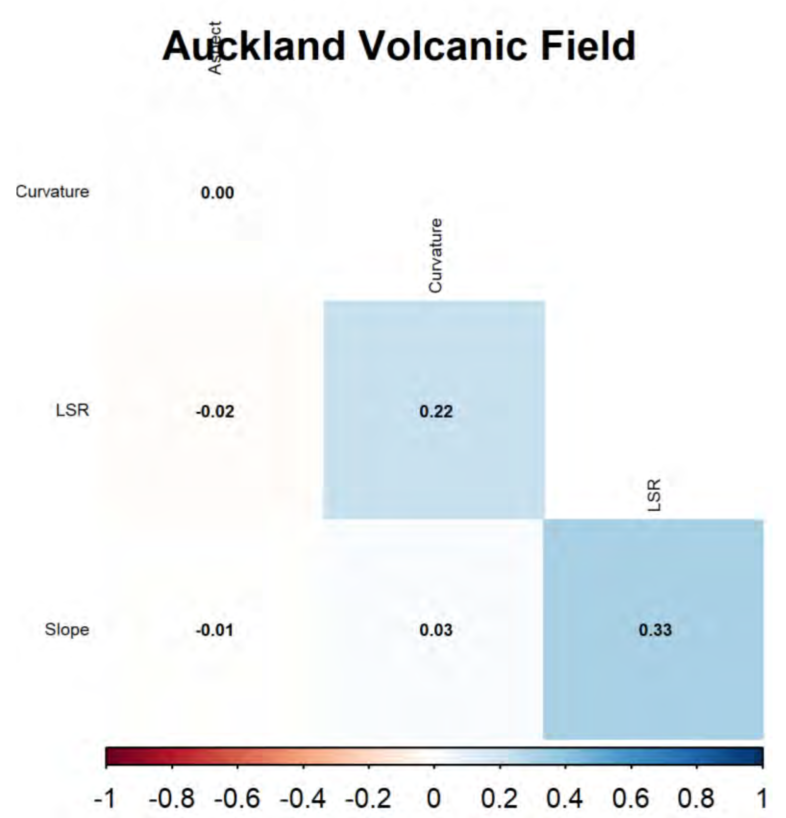
	Land area comparison					
	Auckland Volcanic Field					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	80.4%	78.4%	75.0%	72.3%	85.1%	83.6%
Low	14.6%	16.0%	6.2%	6.9%	5.0%	5.6%
Moderate	3.3%	3.6%	6.3%	7.1%	4.3%	4.4%
High	1.7%	2.0%	6.2%	6.6%	3.1%	3.5%
Very High			6.3%	7.1%	2.6%	2.9%

	Landslide inventory density (landslide area per class/total landslide area per region)					
	Auckland Volcanic Field					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	25.2%	19.3%	19.7%	15.5%	29.0%	25.6%
Low	24.8%	23.5%	6.3%	5.0%	7.6%	5.9%
Moderate	24.8%	23.1%	4.6%	7.6%	10.5%	7.6%
High	25.2%	34.0%	13.4%	10.5%	17.2%	19.3%
Very High			55.9%	61.3%	35.7%	41.6%

	Landslide number density (landslide cells/total cells per region)					
	Auckland Volcanic Field					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	0.1%	0.0%	0.0%	0.0%	0.1%	0.1%
Low	0.3%	0.3%	0.2%	0.1%	0.3%	0.2%
Moderate	1.3%	1.1%	0.1%	0.2%	0.4%	0.3%
High	2.5%	2.9%	0.4%	0.3%	1.0%	1.0%
Very High			1.5%	1.5%	2.4%	2.4%

VARIABLE CORRELATIONS

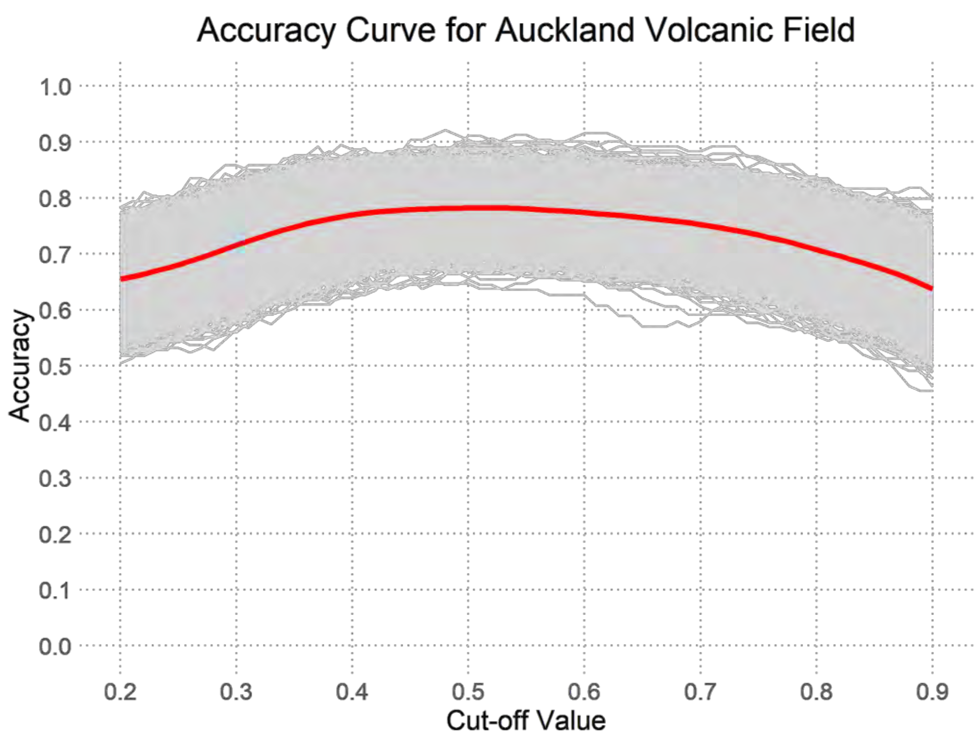
Continuous Variables



Categorical Variables

GeolUnit_vs_Geomorphon	0.084554307
GeolUnit_vs_DistanceToStream	0.058868842
GeolUnit_vs_LCDB	0.221479829
GeolUnit_vs_OLFP	0.039513073
Geomorphon_vs_DistanceToStream	0.108020583
Geomorphon_vs_LCDB	0.155052672
Geomorphon_vs_OLFP	0.178615276
DistanceToStream_vs_LCDB	0.039330926
DistanceToStream_vs_OLFP	0.038120700
LCDB_vs_OLFP	0.041109518

ACCURACY PLOT

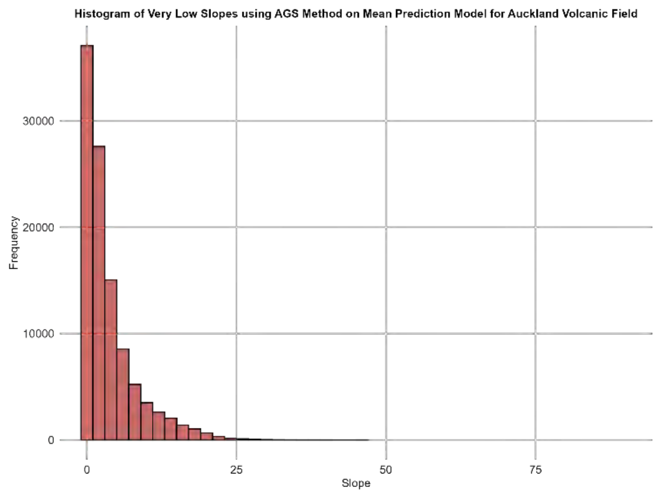


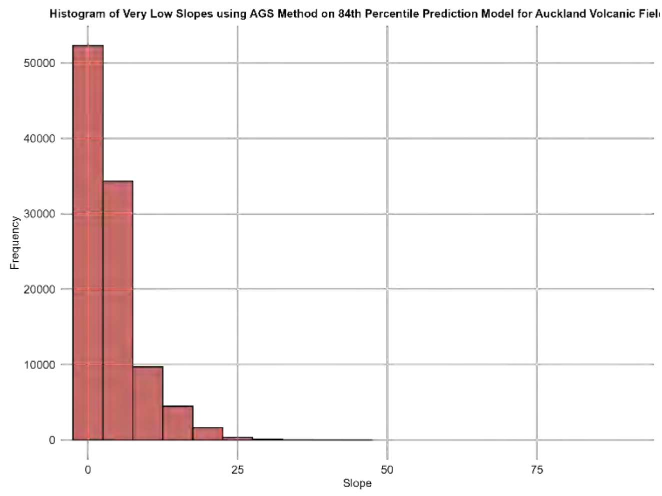
SLOPE ANGLE DISTRIBUTIONS

METHOD 1 (AGS)

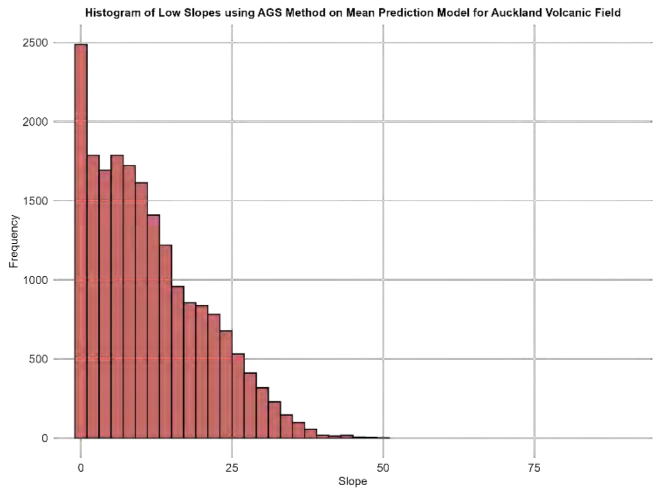
Mean predictions | 84th percentile predictions

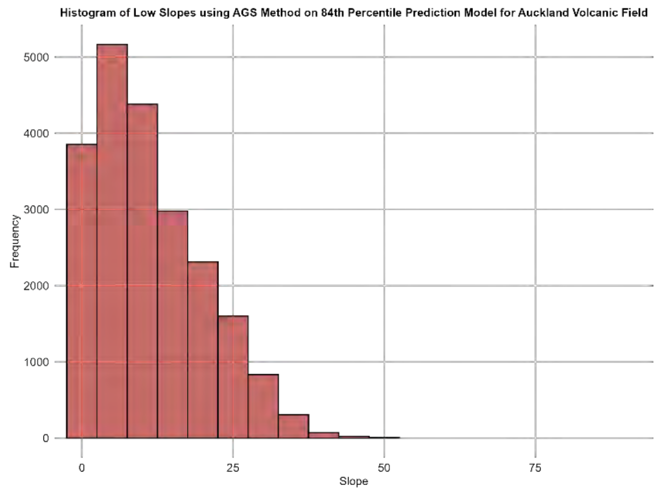
Very Low



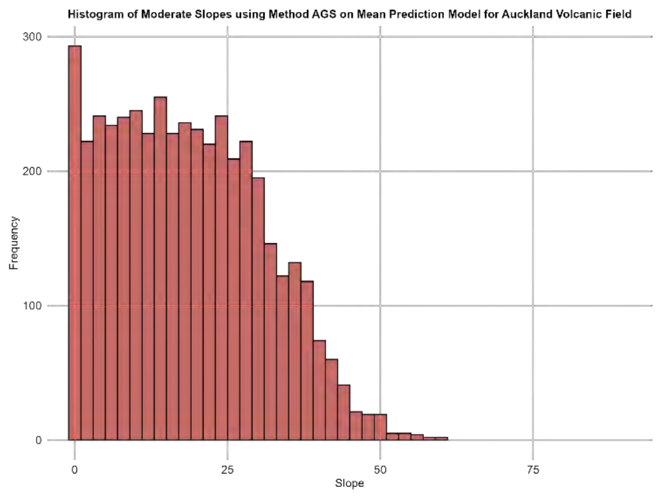


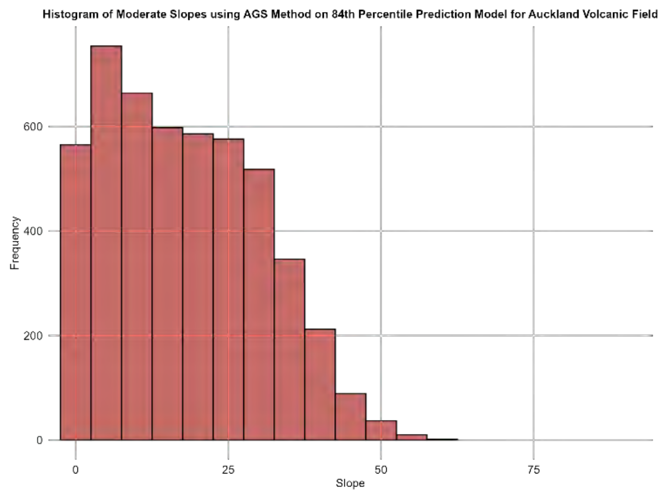
Low



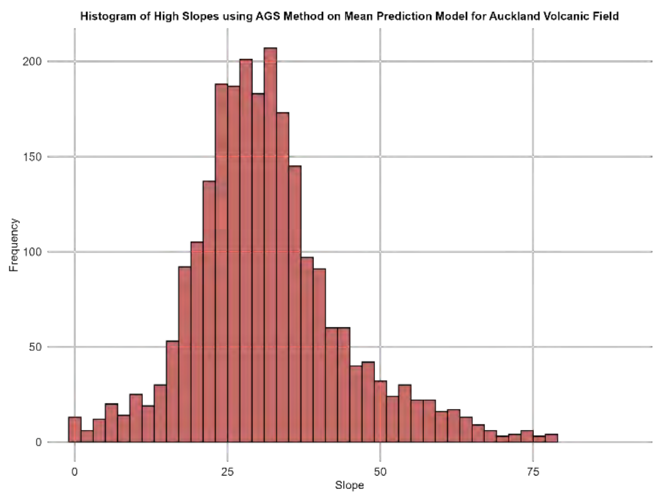


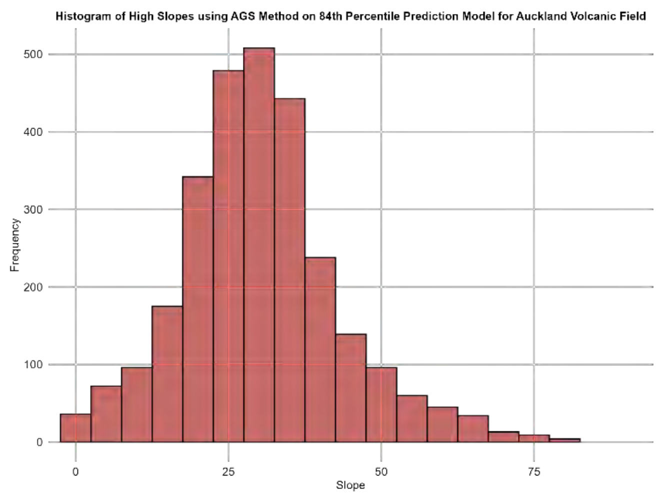
Moderate





High

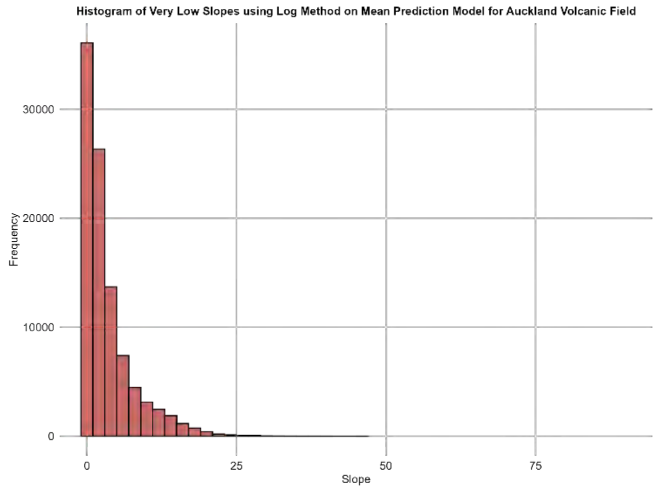


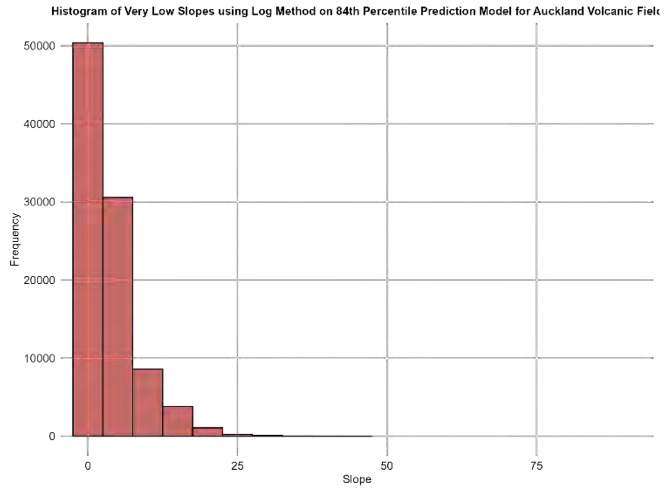


METHOD 2 (LOG BINS)

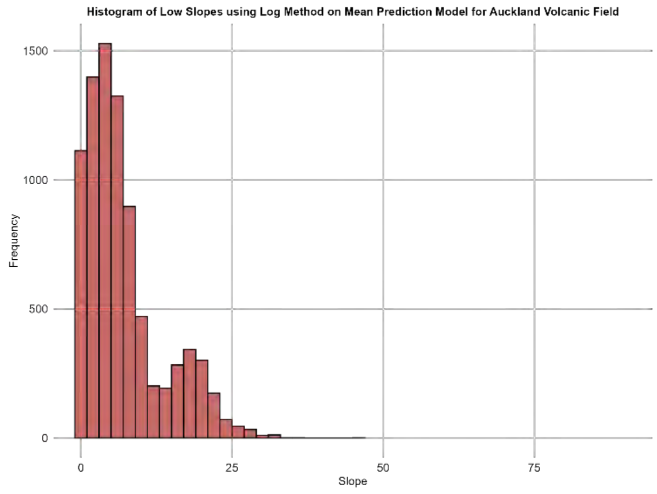
Mean predictions | 84th percentile predictions

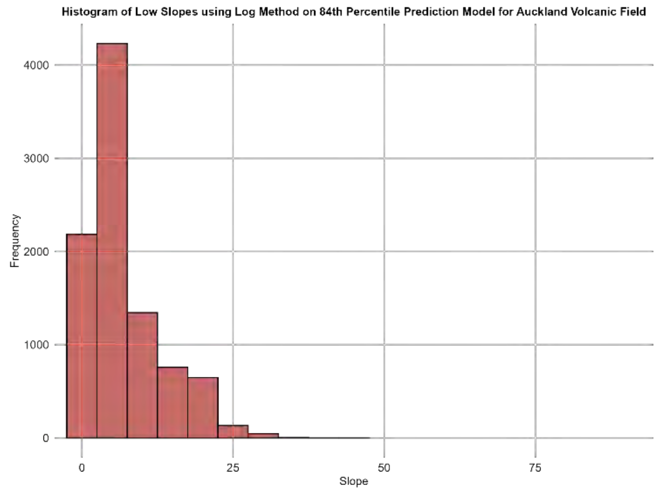
Very Low



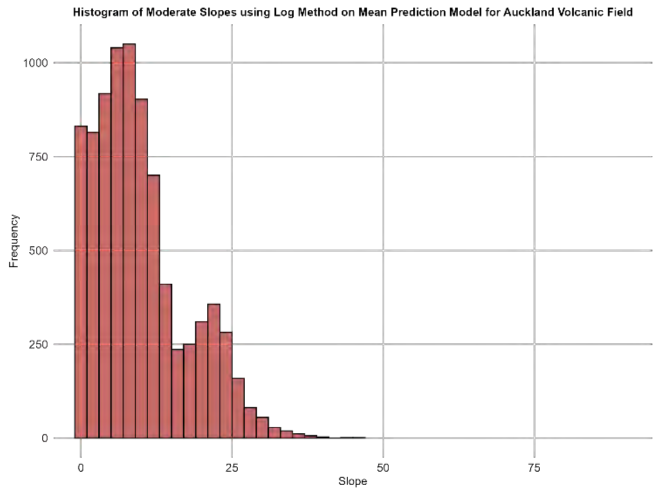


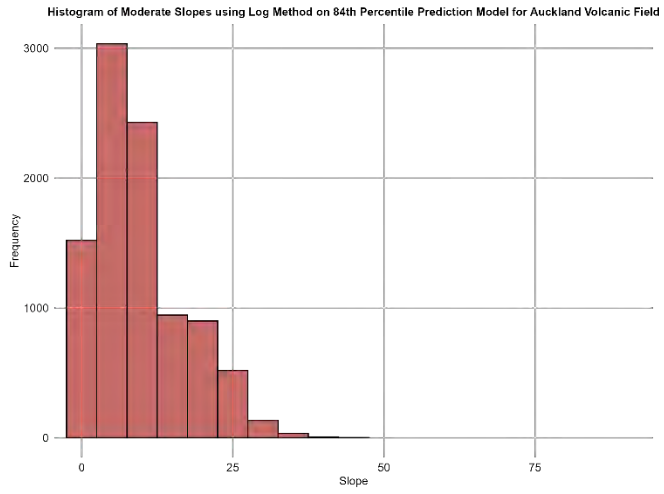
Low



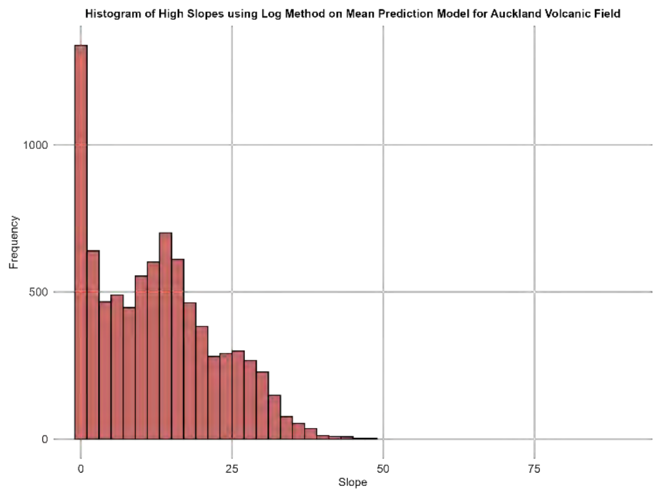


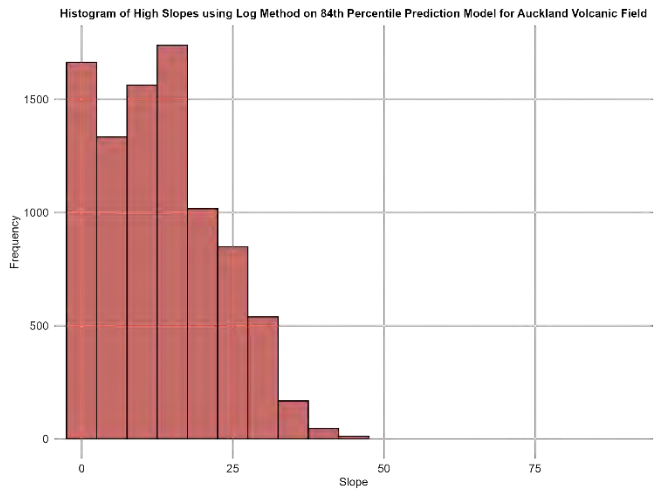
Moderate



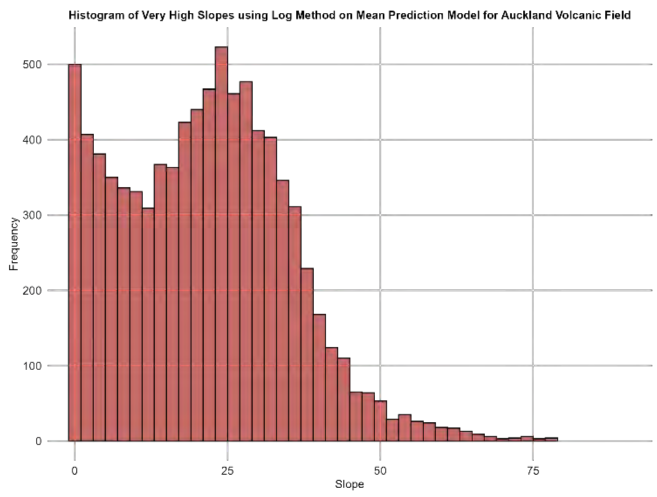


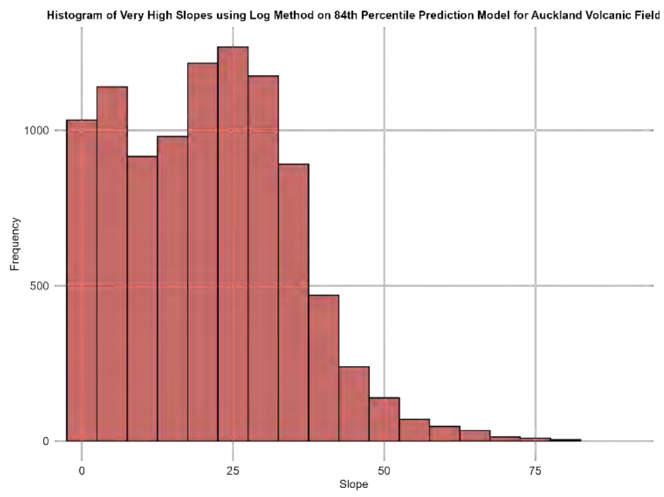
High





Very High



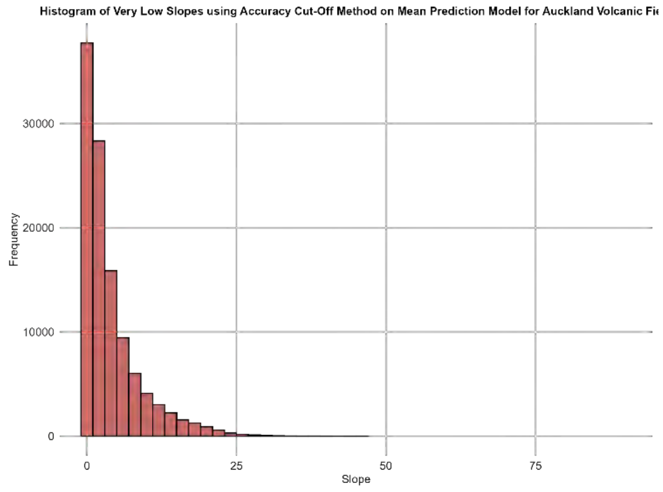


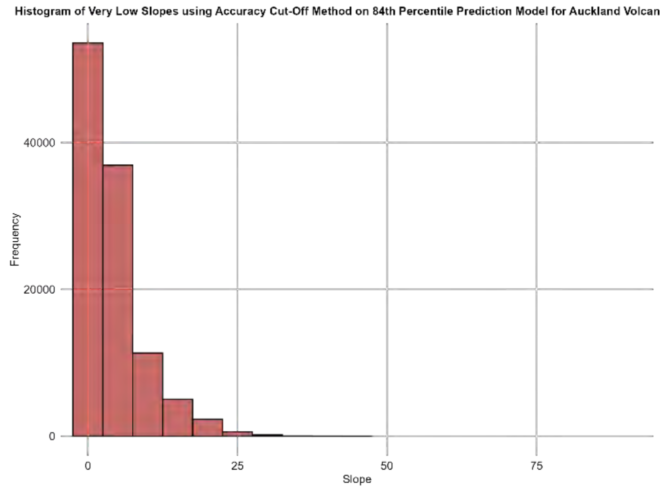
METHOD 3 (ACCURACY CUT-OFF)

Mean predictions

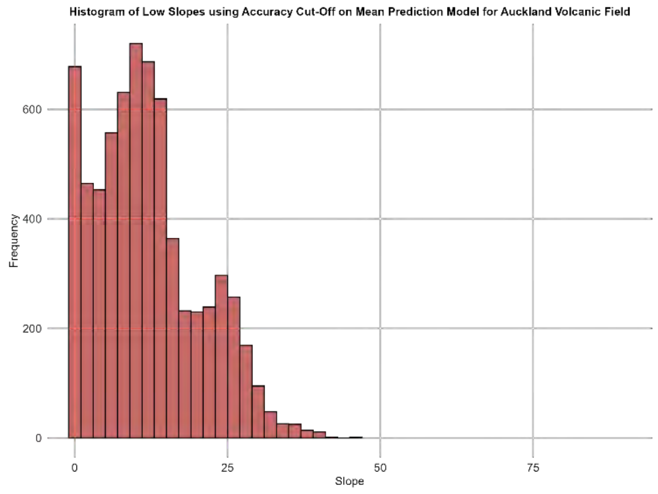
84th percentile predictions

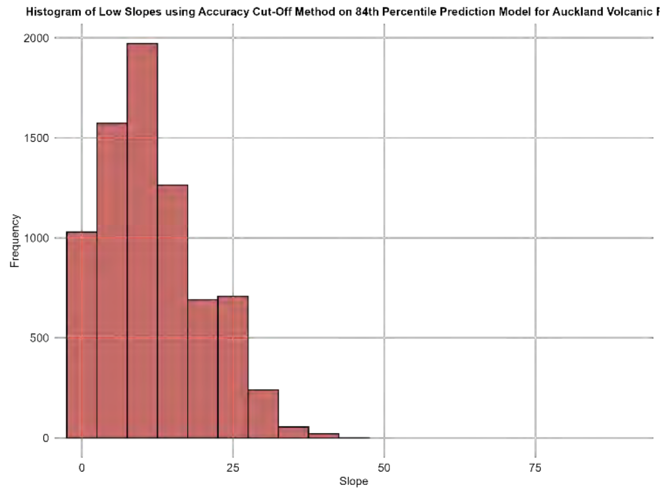
Very Low



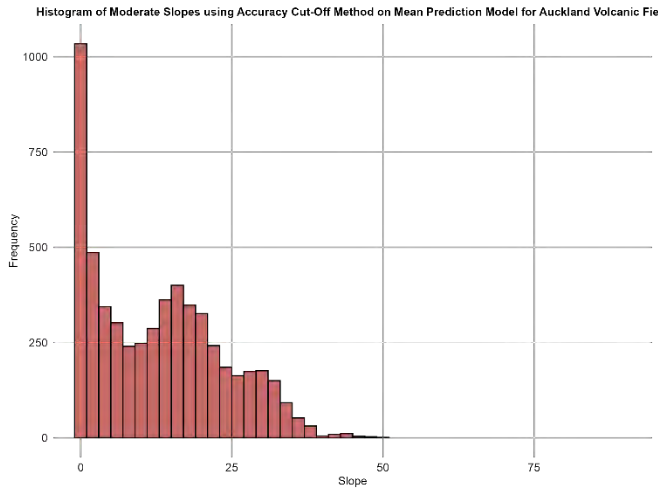


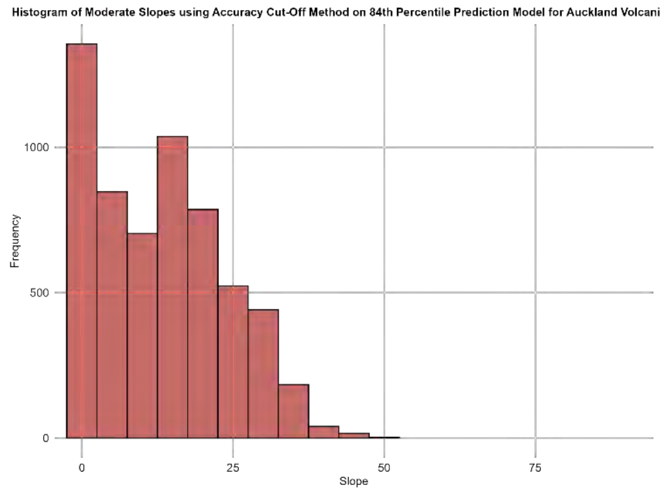
Low



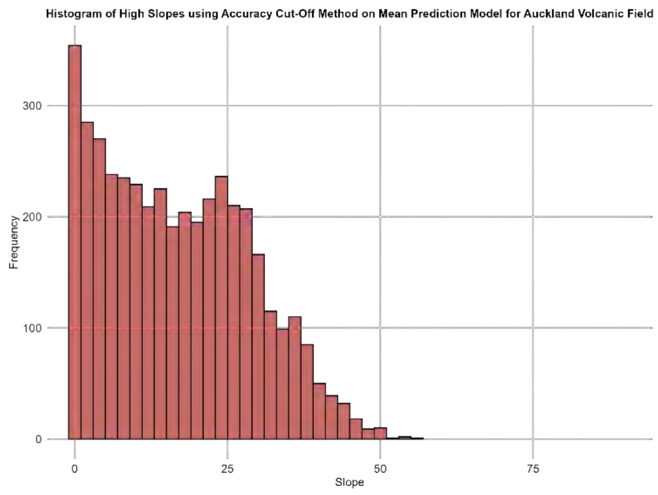


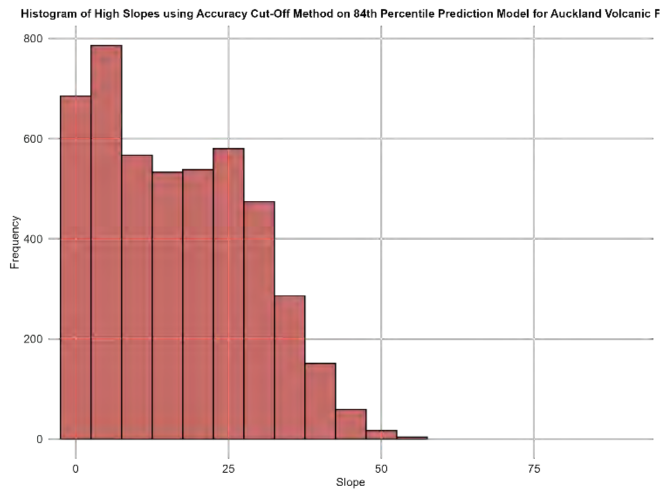
Moderate



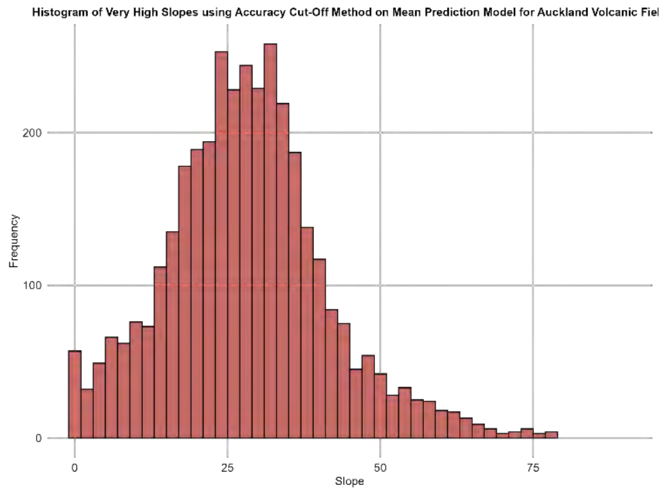


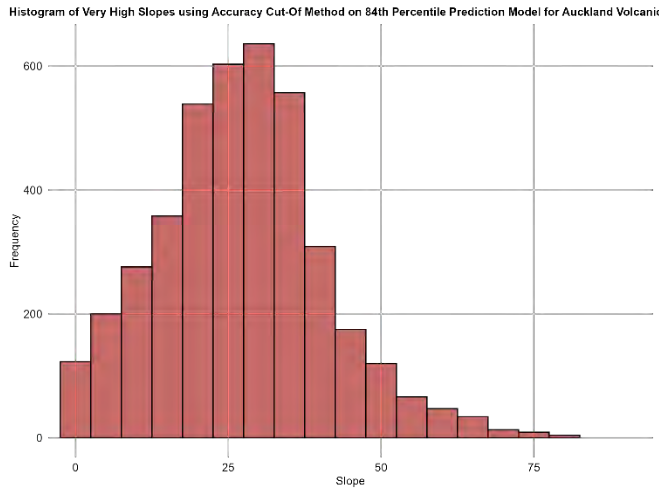
High





Very High



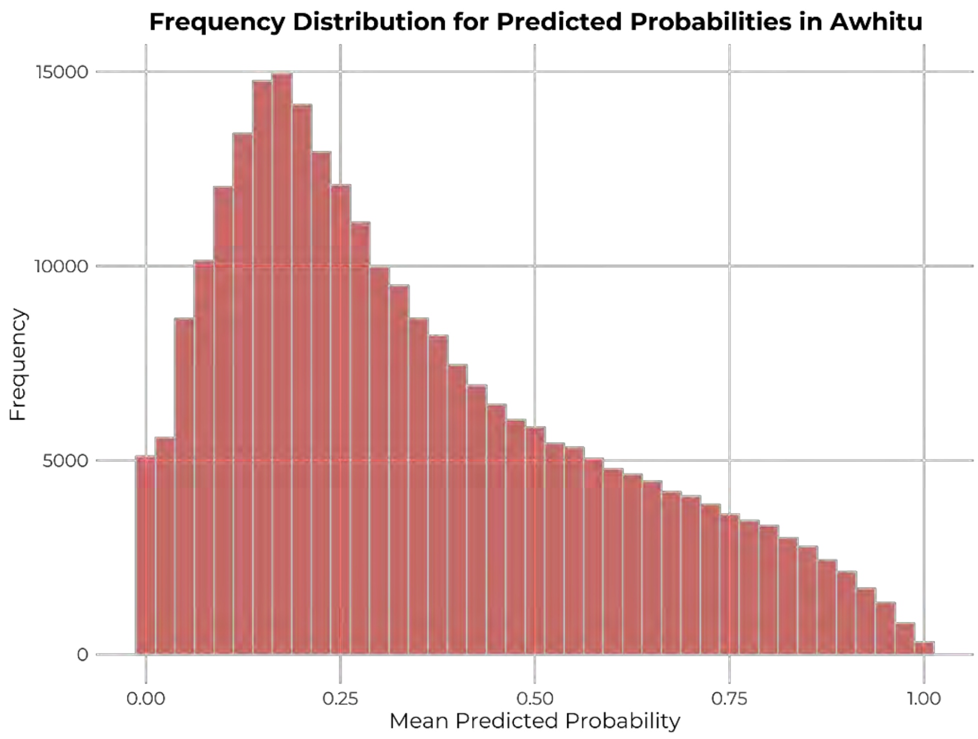


AWHITU

MODEL COEFFICIENTS

Variable	Mean Coefficient	Standard Error	95% Confidence Interval	
			Upper Bound	Lower Bound
Intercept	-16.1226	0.081275	-15.9632	-16.2819
Aspect	0.070548	0.000347	0.071228	0.069867
Curvature	0.093731	0.000314	0.094347	0.093115
Geomorphon2	10.95693	0.011788	10.98004	10.93383
Geomorphon3	10.98386	0.011669	11.00674	10.96099
Geomorphon4	8.86067	0.040308	8.939692	8.781648
Geomorphon5	11.29295	0.01165	11.31579	11.27011
Geomorphon6	11.84168	0.011619	11.86446	11.8189
Geomorphon7	12.28456	0.011649	12.3074	12.26172
Geomorphon8	10.49465	0.024451	10.54258	10.44671
Geomorphon9	12.69833	0.011629	12.72112	12.67553
Geomorphon10	13.25001	0.011835	13.27321	13.22681
DistanceToStream10	0.059	0.003855	0.066558	0.051443
DistanceToStream20	0.237307	0.003309	0.243794	0.23082
DistanceToStream9999	-0.16095	0.002894	-0.15527	-0.16662
LCDB1	3.158561	0.075517	3.306607	3.010515
LCDB2	4.74669	0.075625	4.894947	4.598432
LCDB3	3.306437	0.075575	3.454597	3.158277
LCDB4	3.842343	0.075495	3.990347	3.69434
LCDB5	-8.63862	0.084191	-8.47356	-8.80368
LCDB7	2.338235	0.075941	2.487112	2.189358
LocalSlopeRelief	0.741062	0.000525	0.742092	0.740033
Slope	0.858896	0.000419	0.859717	0.858074
OLFP10	0.009026	0.002312	0.013558	0.004493
OLFP9999	0.061024	0.001862	0.064675	0.057373
GeolUnit4	-0.27609	0.001983	-0.2722	-0.27998
GeolUnit8	-13.4001	0.048196	-13.3053	-13.4949
GeolUnit9	0.317154	0.079938	0.473935	0.160373

PROBABILITY DISTRIBUTION



AREA COMPARISONS

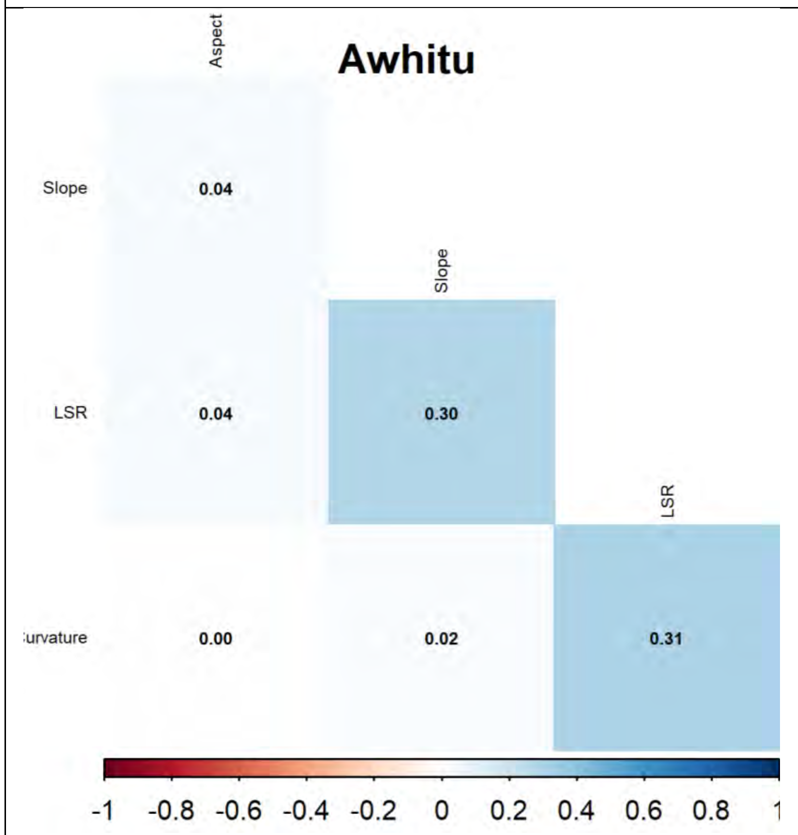
	Land area comparison					
	Awhitu					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	20.8%	18.6%	75.0%	73.0%	42.1%	39.1%
Low	33.2%	32.5%	6.2%	6.6%	30.2%	31.1%
Moderate	35.3%	36.9%	6.2%	6.6%	10.7%	11.2%
High	10.8%	12.0%	6.2%	6.7%	9.2%	9.7%
Very High			6.3%	7.1%	7.8%	8.8%

	Landslide inventory density (landslide area per class/total landslide area per region)					
	Awhitu					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	1.0%	0.8%	25.3%	4.2%	5.1%	23.4%
Low	9.0%	7.6%	8.9%	16.5%	17.6%	7.8%
Moderate	40.0%	38.5%	11.5%	13.5%	14.3%	11.4%
High	50.0%	53.1%	18.0%	21.9%	21.8%	18.2%
Very High			36.4%	44.0%	41.2%	39.1%

	Landslide number density (landslide cells/total cells per region)					
	Awhitu					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	0.1%	0.1%	0.5%	0.5%	0.2%	0.2%
Low	0.4%	0.3%	2.1%	1.8%	0.9%	0.8%
Moderate	1.7%	1.5%	2.7%	2.6%	2.0%	1.8%
High	6.9%	6.5%	4.3%	4.0%	3.5%	3.3%
Very High			8.6%	8.2%	7.8%	7.4%

VARIABLE CORRELATIONS

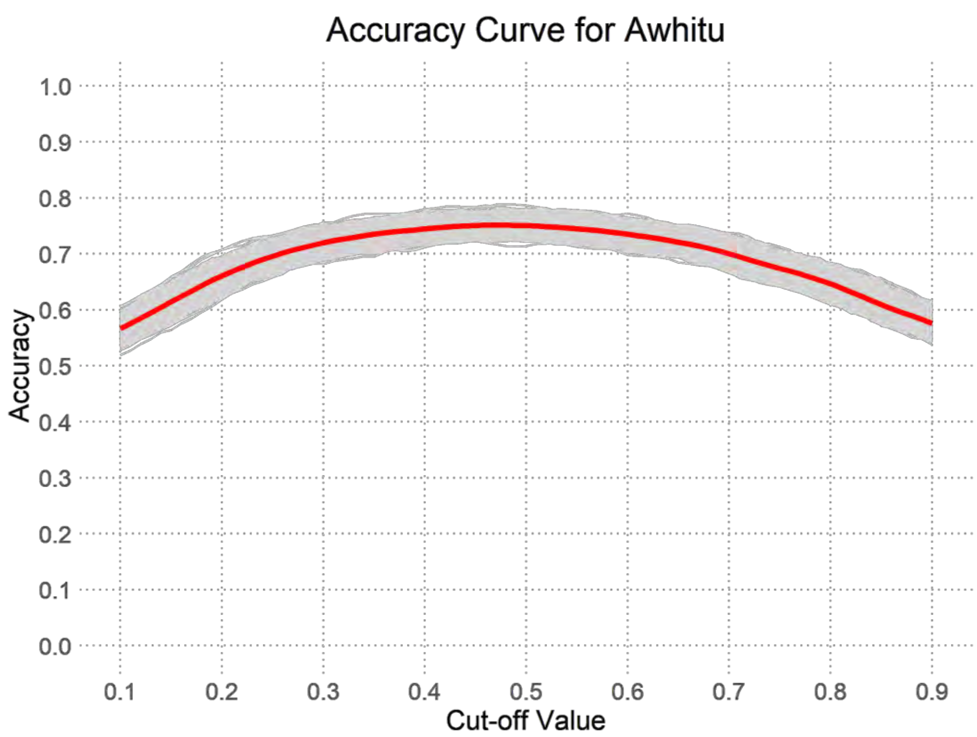
Continuous Variables



Categorical Variables

GeolUnit_vs_Geomorphon	0.176301272
GeolUnit_vs_DistanceToStream	0.029067738
GeolUnit_vs_LCDB	0.145701448
GeolUnit_vs_OLFP	0.062536643
Geomorphon_vs_DistanceToStream	0.237016045
Geomorphon_vs_LCDB	0.201354013
Geomorphon_vs_OLFP	0.256730769
DistanceToStream_vs_LCDB	0.031768362
DistanceToStream_vs_OLFP	0.163066891
LCDB_vs_OLFP	0.045432188

ACCURACY PLOT



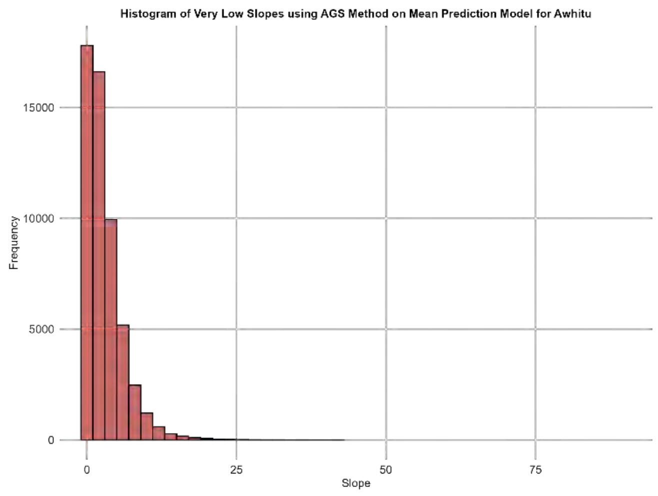
SLOPE ANGLE DISTRIBUTIONS

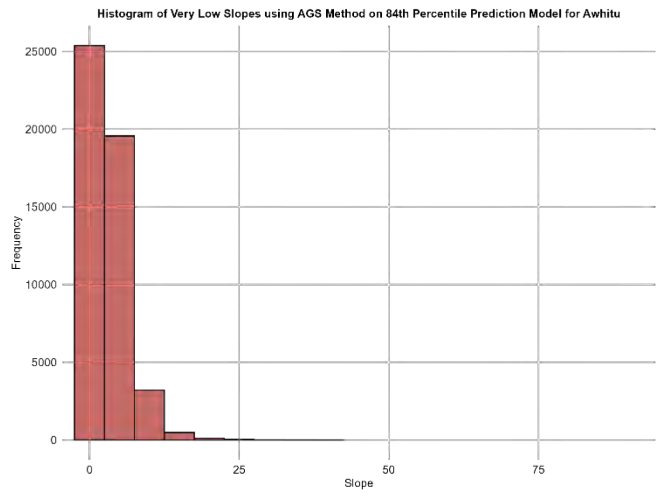
METHOD 1 (AGS)

Mean predictions

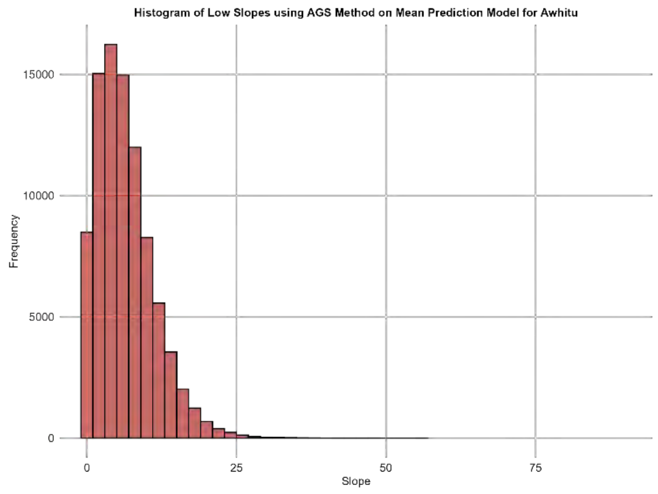
84th percentile predictions

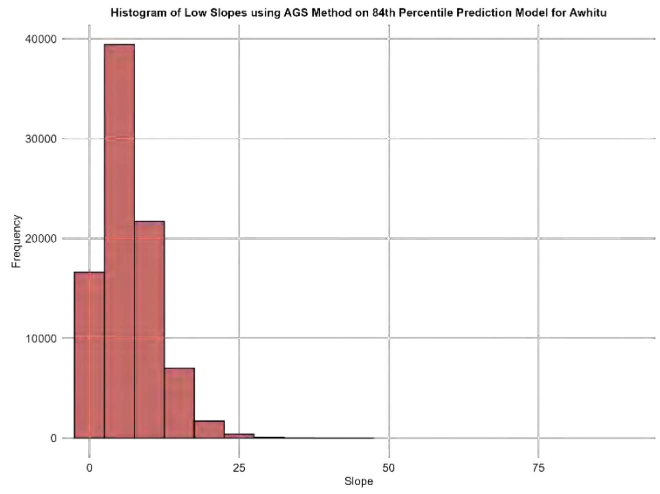
Very Low



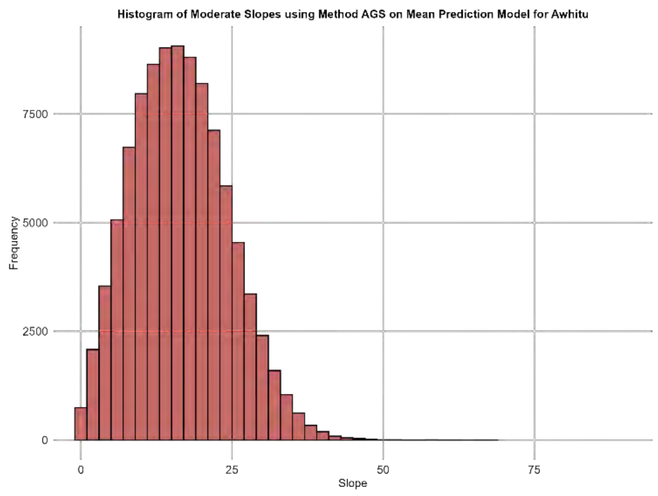


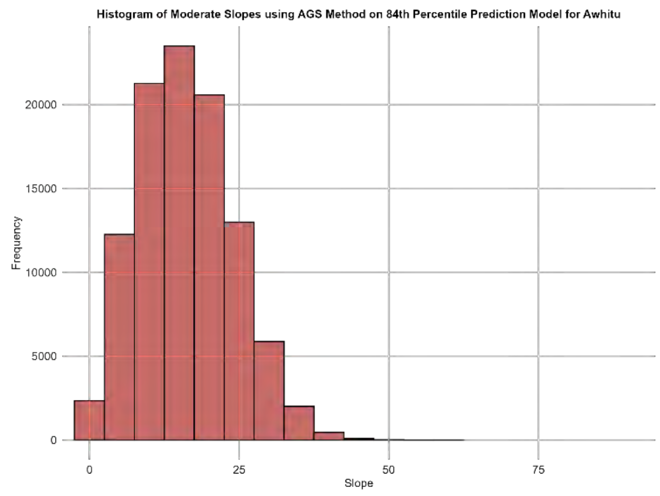
Low



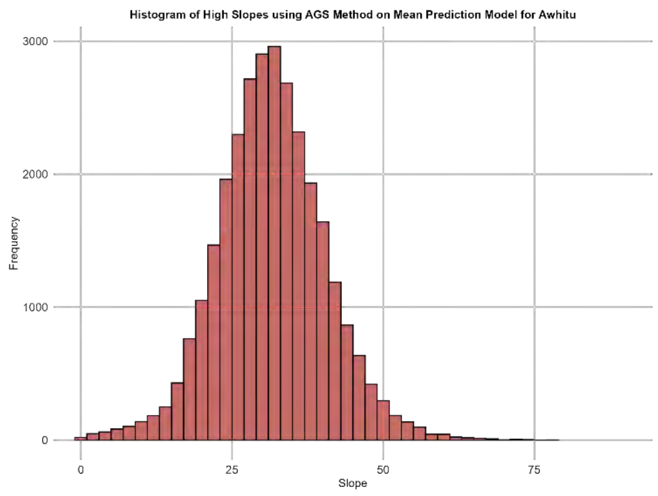


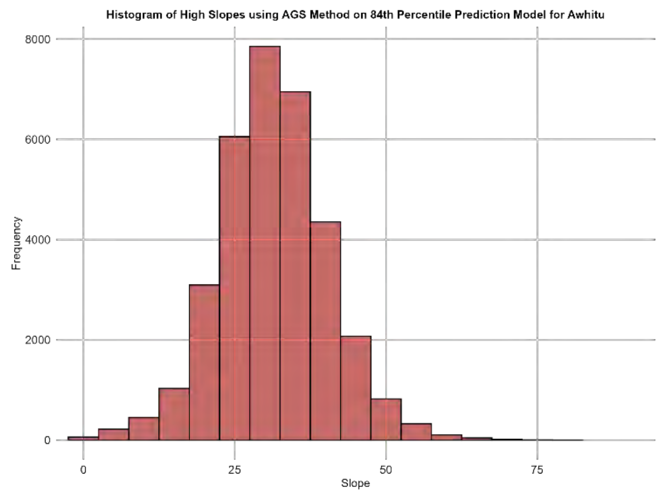
Moderate





High



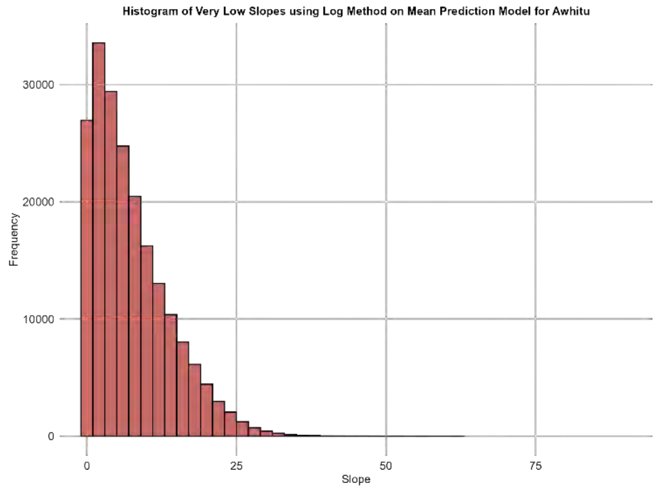


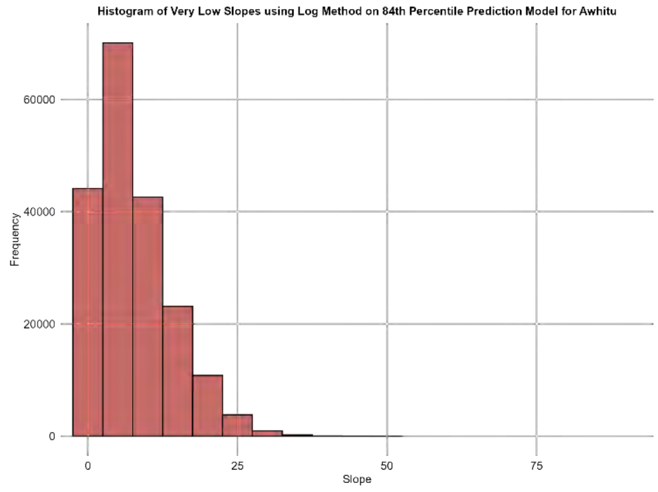
METHOD 2 (LOG BINS)

Mean predictions

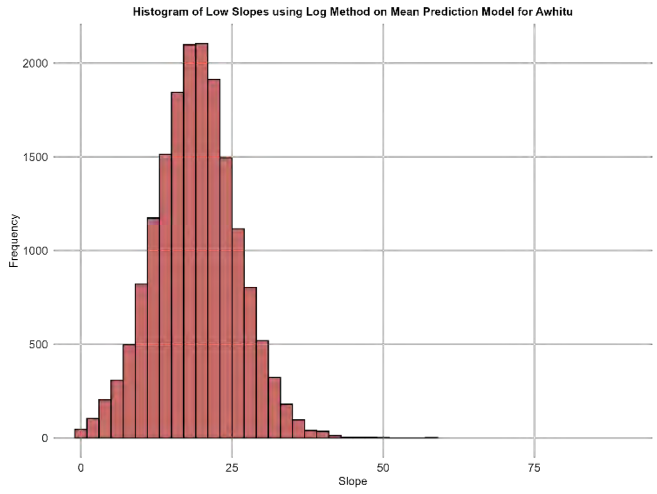
84th percentile predictions

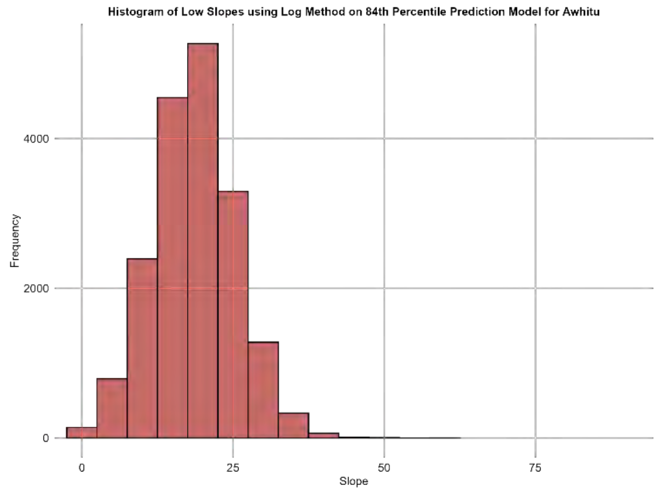
Very Low



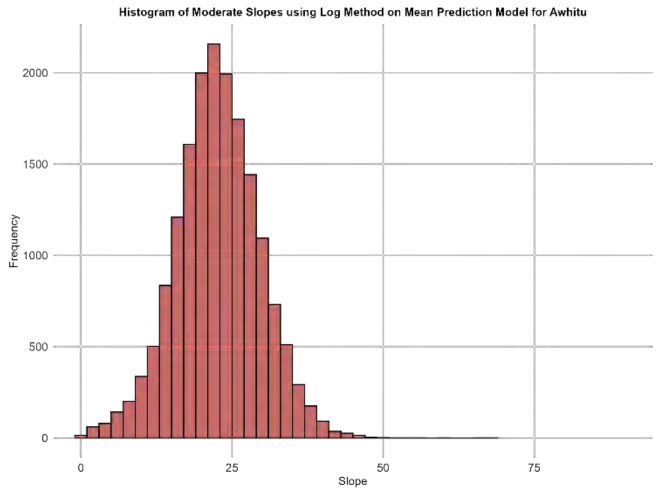


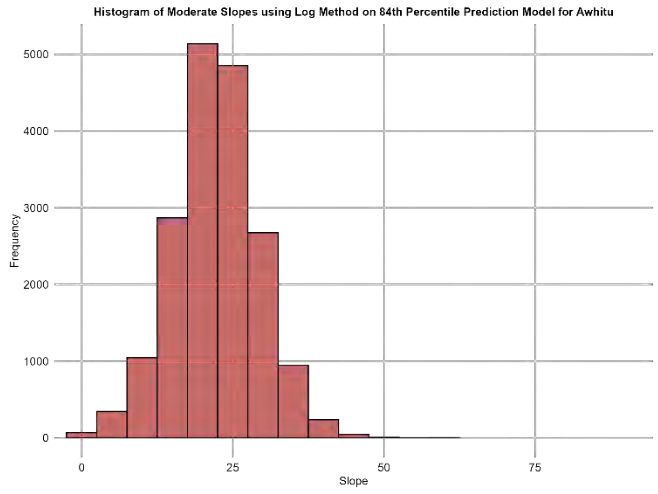
Low



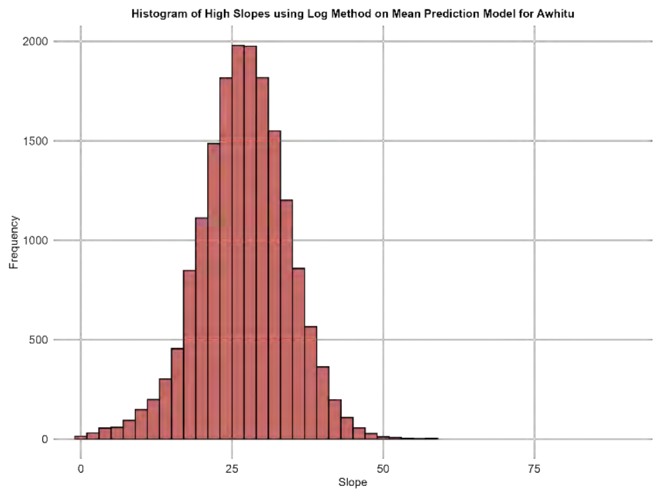


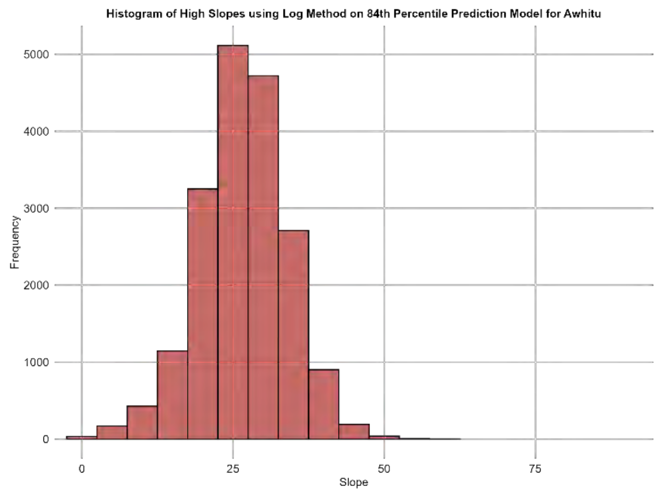
Moderate



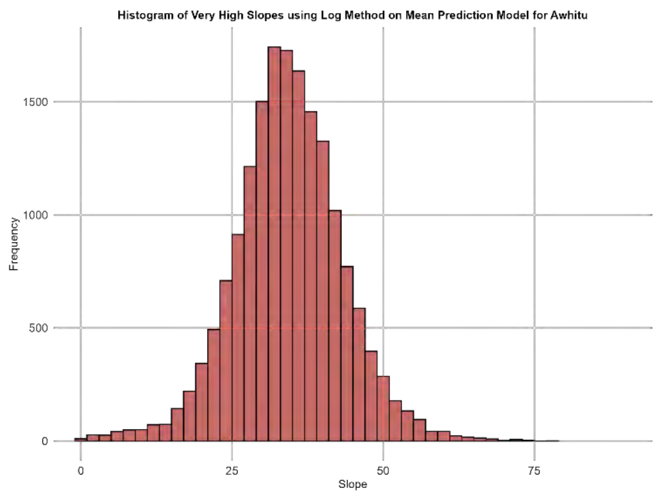


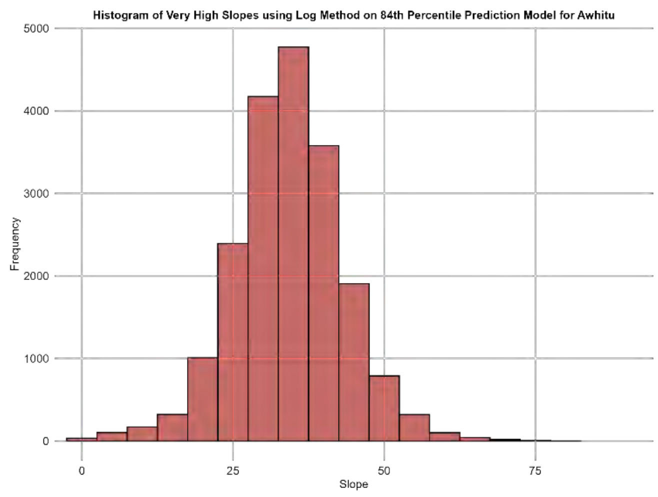
High





Very High

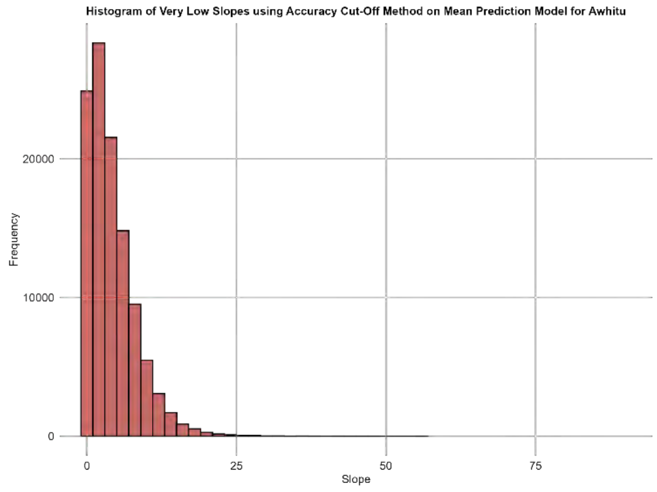


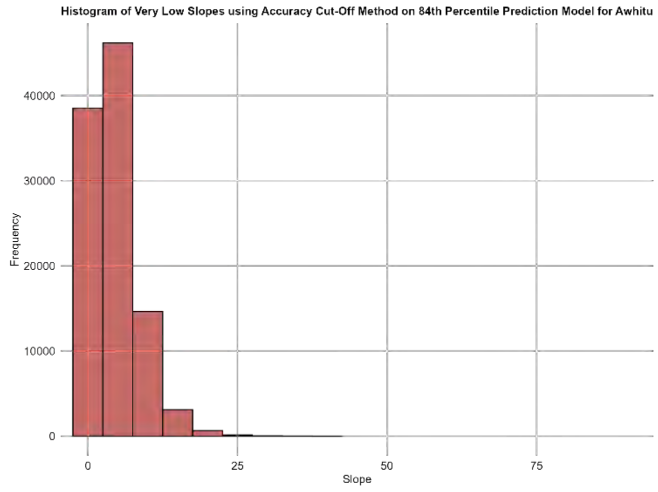


METHOD 3 (ACCURACY CUT-OFF)

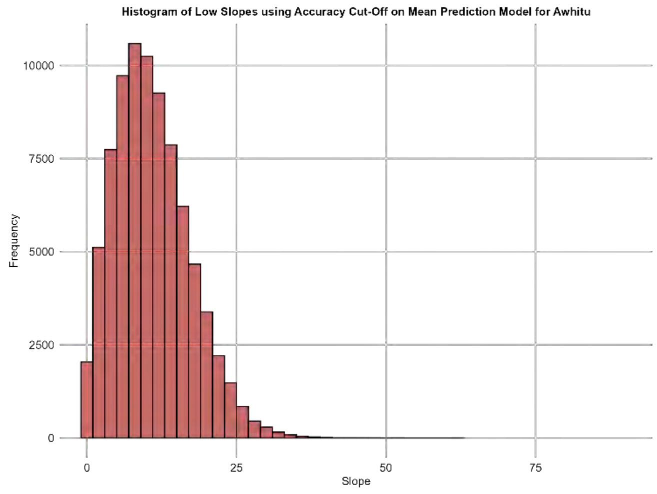
Mean predictions | 84th percentile predictions

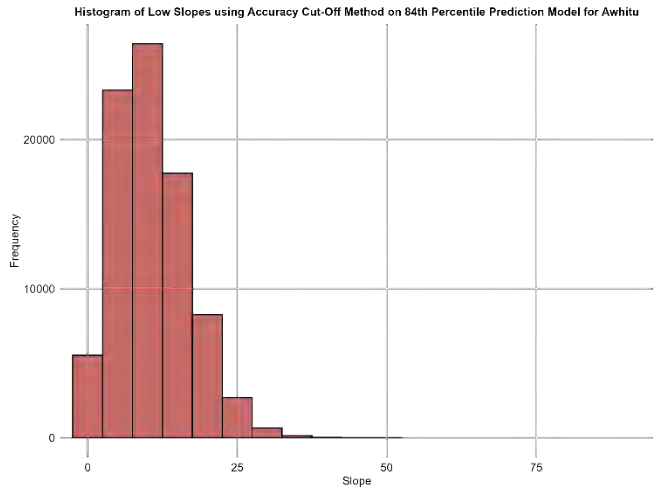
Very Low



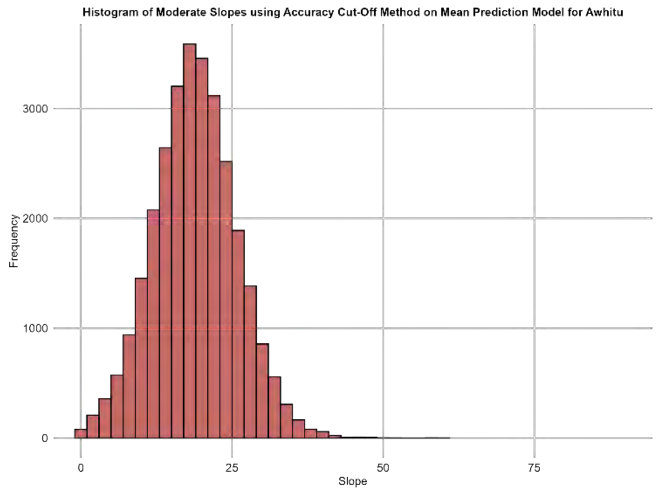


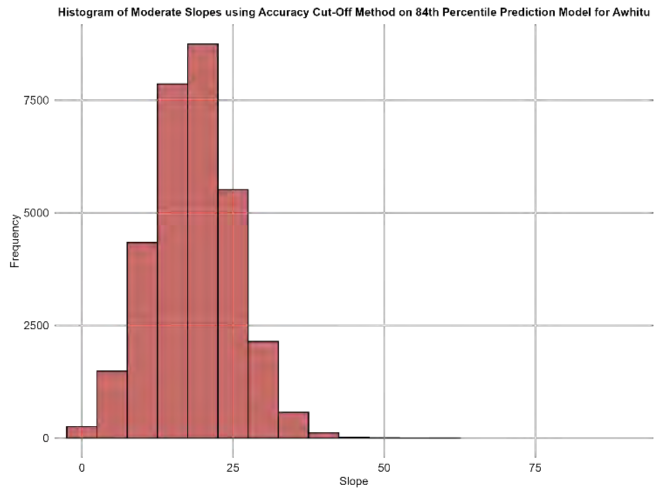
Low



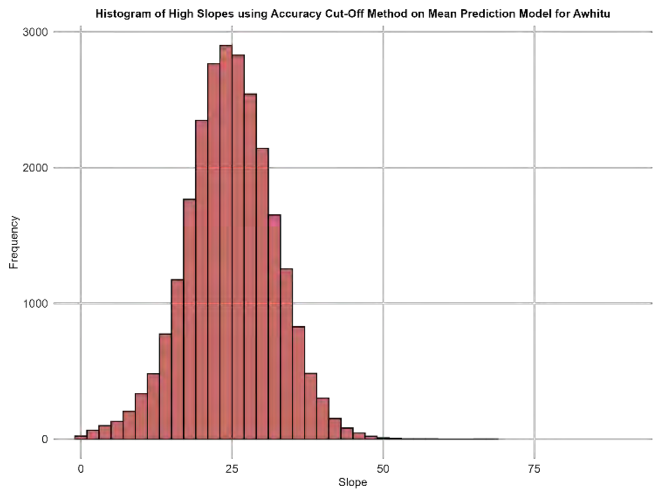


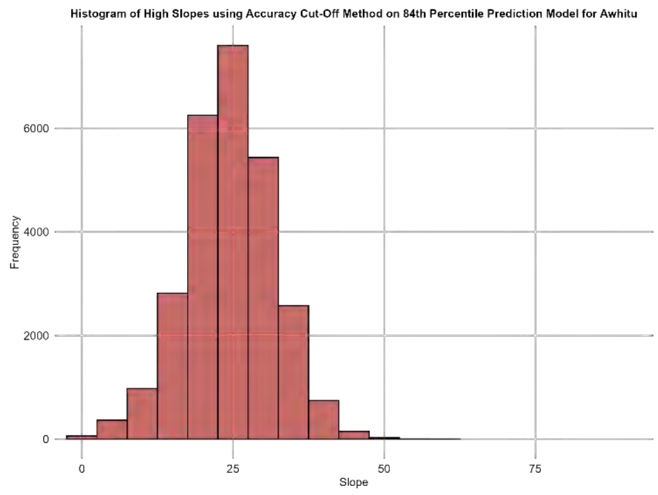
Moderate



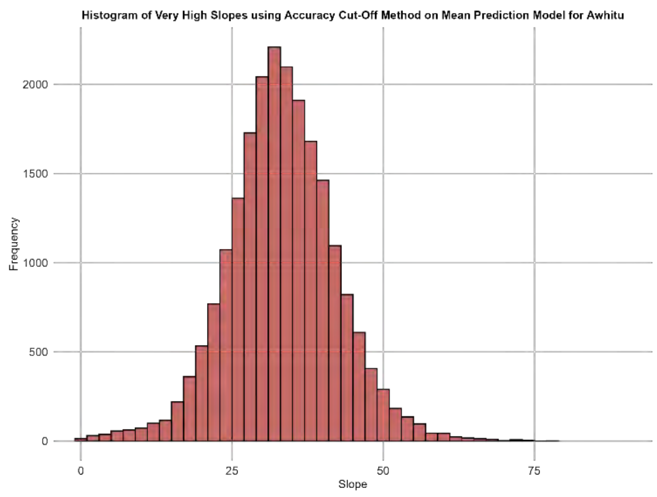


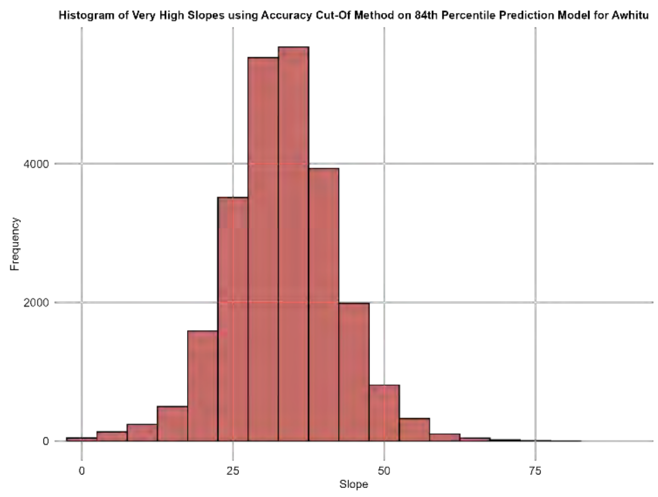
High





Very High



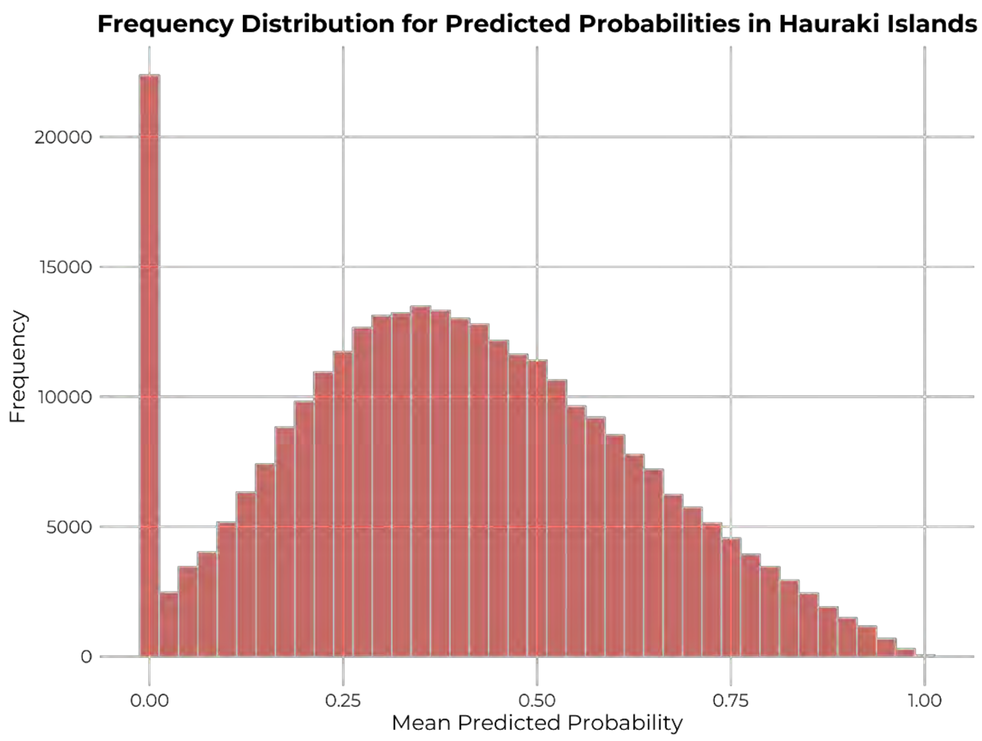


HAURAKI ISLANDS

MODEL COEFFICIENTS

Variable	Mean Coefficient	Standard Error	95% Confidence Interval	
			Upper Bound	Lower Bound
Intercept	-4.8E+11	4.76E+11	4.57E+11	-1.4E+12
Aspect	-2.3E+10	2.3E+10	2.21E+10	-6.8E+10
Curvature	-4.4E+10	4.39E+10	4.22E+10	-1.3E+11
GeolUnit2	-2.3E+11	2.31E+11	2.22E+11	-6.9E+11
GeolUnit4	-1.2E+11	1.18E+11	1.14E+11	-3.5E+11
GeolUnit5	3.4E+10	3.4E+10	1.01E+11	-3.3E+10
Geomorphon2	2.54E+09	2.54E+09	7.51E+09	-2.4E+09
Geomorphon3	3.08E+11	3.08E+11	9.12E+11	-3E+11
Geomorphon5	-2.2E+11	2.15E+11	2.07E+11	-6.4E+11
Geomorphon6	3.78E+11	3.78E+11	1.12E+12	-3.6E+11
Geomorphon7	5.12E+11	5.12E+11	1.52E+12	-4.9E+11
Geomorphon8	9.61E+10	9.61E+10	2.85E+11	-9.2E+10
Geomorphon9	-1.3E+11	1.29E+11	1.24E+11	-3.8E+11
Geomorphon10	1.255375	0.10083	1.453047	1.057703
LCDB1	7.01E+11	7.01E+11	2.07E+12	-6.7E+11
LCDB2	2.08E+10	2.08E+10	6.16E+10	-2E+10
LCDB4	-1.4E+11	1.38E+11	1.33E+11	-4.1E+11
LCDB5	2.44E+11	2.44E+11	7.22E+11	-2.3E+11
LCDB6	1.424877	1.46644	4.351904	-1.50215
LCDB7	6.76E+11	6.76E+11	2E+12	-6.5E+11
LocalSlopeRelief	1.23E+11	1.23E+11	3.65E+11	-1.2E+11
Slope	7.9E+10	7.9E+10	2.34E+11	-7.6E+10
OLFP10	-4.5E+10	4.47E+10	4.29E+10	-1.3E+11
OLFP9999	-2.4E+10	2.38E+10	2.28E+10	-7E+10
Geomorphon4	1.70588	0.131985	1.964642	1.447117
LCDB3	7.63E+11	7.63E+11	2.26E+12	-7.3E+11
DistanceToStream10	0.623123	0.127781	0.874387	0.371859
DistanceToStream20	0.828997	0.089836	1.005647	0.652347
DistanceToStream9999	1.16499	0.083718	1.329611	1.000369

PROBABILITY DISTRIBUTION



AREA COMPARISONS

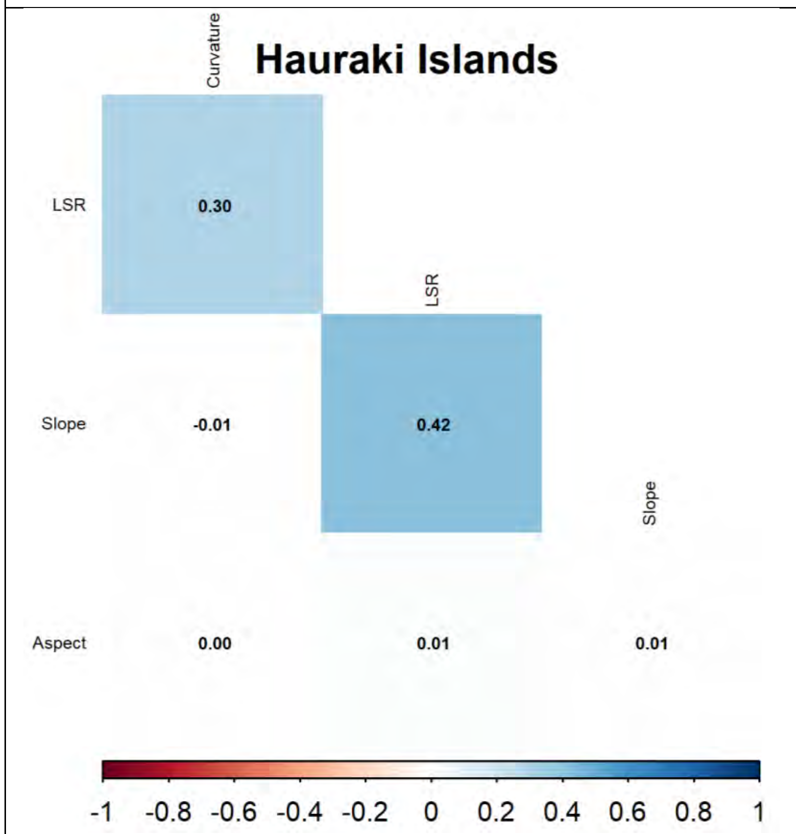
	Land area comparison					
	Hauraki Islands					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	14.6%	12.3%	75.0%	71.2%	25.7%	22.0%
Low	27.3%	24.9%	6.2%	6.8%	45.8%	45.5%
Moderate	43.4%	45.4%	6.2%	7.1%	13.2%	14.4%
High	14.6%	17.4%	6.3%	7.2%	9.6%	11.0%
Very High			6.2%	7.8%	5.7%	7.1%

	Landslide inventory density (landslide area per class/total landslide area per region)					
	Hauraki Islands					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	1.0%	0.6%	31.9%	25.6%	3.9%	2.3%
Low	9.0%	6.7%	9.0%	8.2%	24.3%	20.7%
Moderate	40.0%	33.1%	14.2%	12.1%	19.8%	16.5%
High	49.9%	59.5%	19.0%	18.9%	28.3%	28.2%
Very High			25.9%	35.2%	23.7%	32.3%

	Landslide number density (landslide cells/total cells per region)					
	Hauraki Islands					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%
Low	0.1%	0.1%	0.4%	0.3%	0.1%	0.1%
Moderate	0.3%	0.2%	0.6%	0.5%	0.4%	0.3%
High	0.9%	0.9%	0.8%	0.7%	0.8%	0.7%
Very High			1.1%	1.3%	1.2%	1.3%

VARIABLE CORRELATIONS

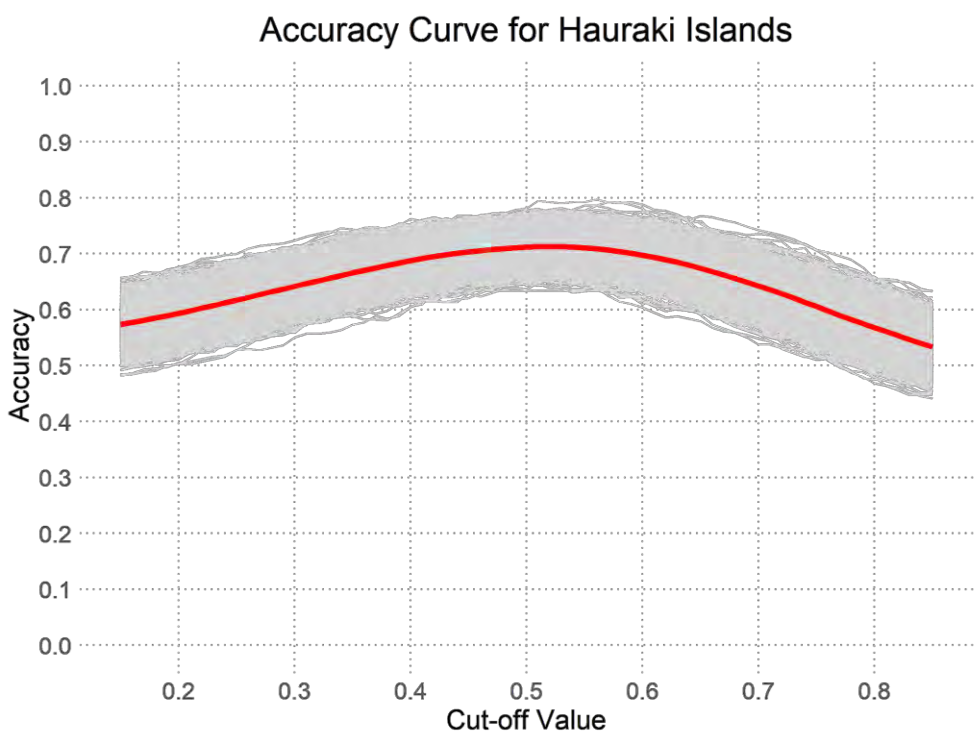
Continuous Variables



Categorical Variables

GeolUnit_vs_Geomorphon	0.364511774
GeolUnit_vs_DistanceToStream	0.014618244
GeolUnit_vs_LCDB	0.361623675
GeolUnit_vs_OLFP	0.051649943
Geomorphon_vs_DistanceToStream	0.210261406
Geomorphon_vs_LCDB	0.221141870
Geomorphon_vs_OLFP	0.277601847
DistanceToStream_vs_LCDB	0.023552705
DistanceToStream_vs_OLFP	0.133971034
LCDB_vs_OLFP	0.034655649

ACCURACY PLOT



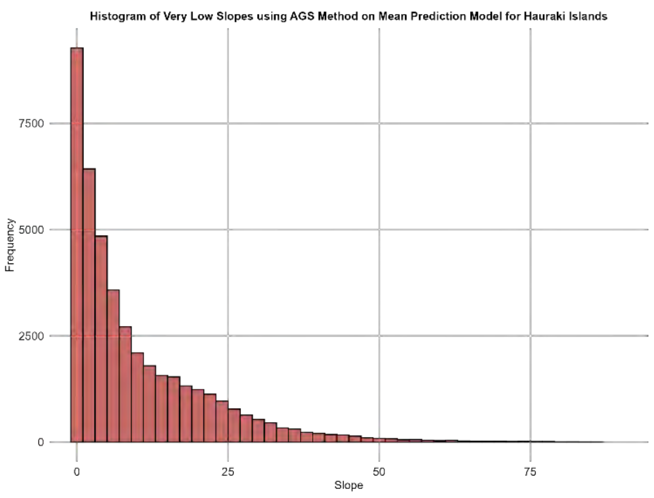
SLOPE ANGLE DISTRIBUTIONS

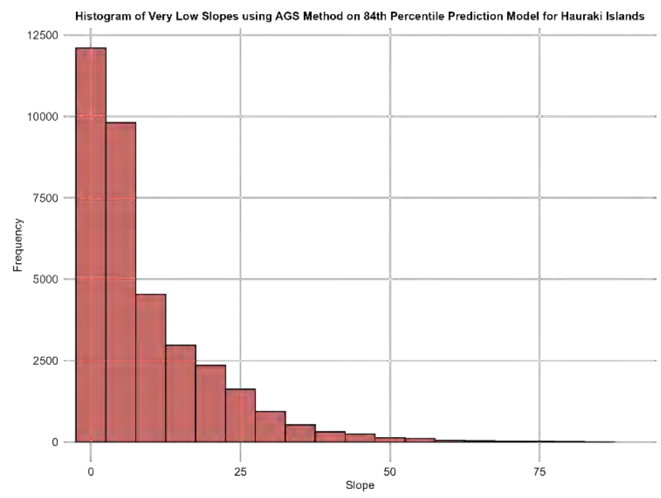
METHOD 1 (AGS)

Mean predictions

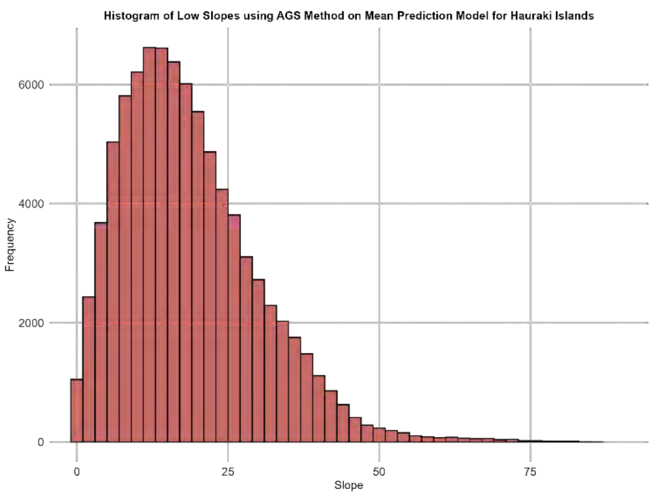
84th percentile predictions

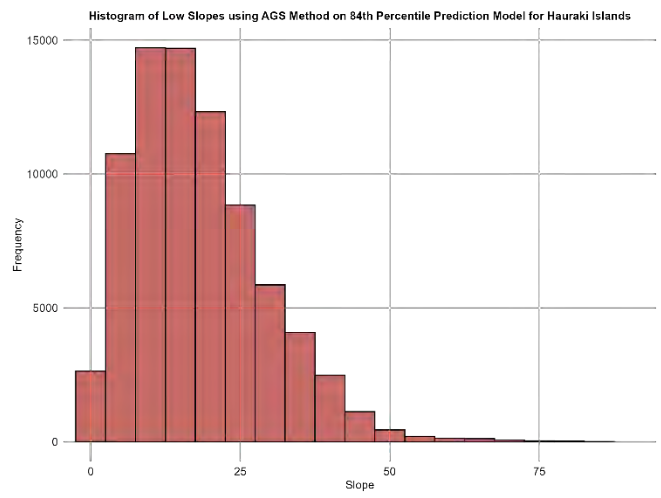
Very Low



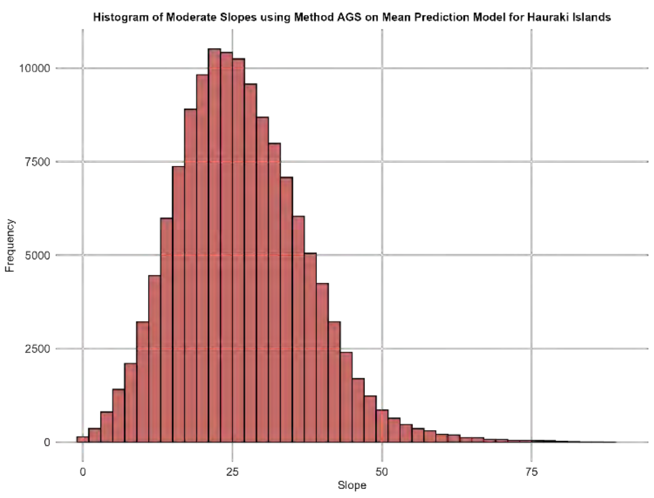


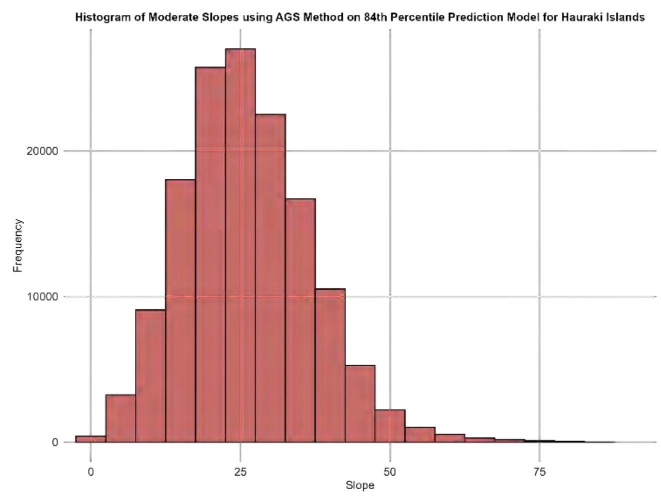
Low



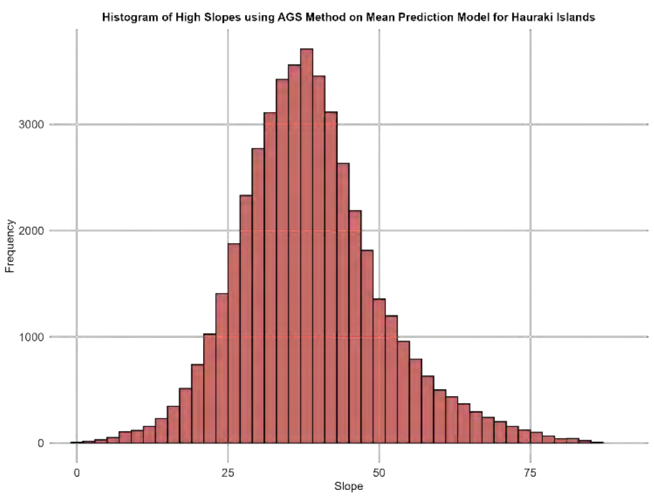


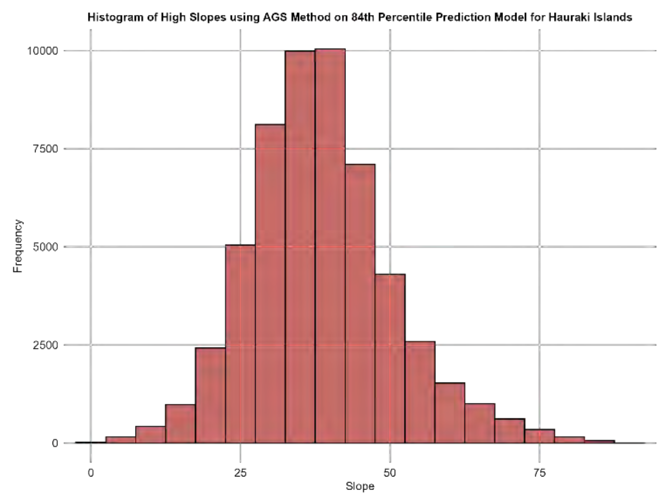
Moderate





High

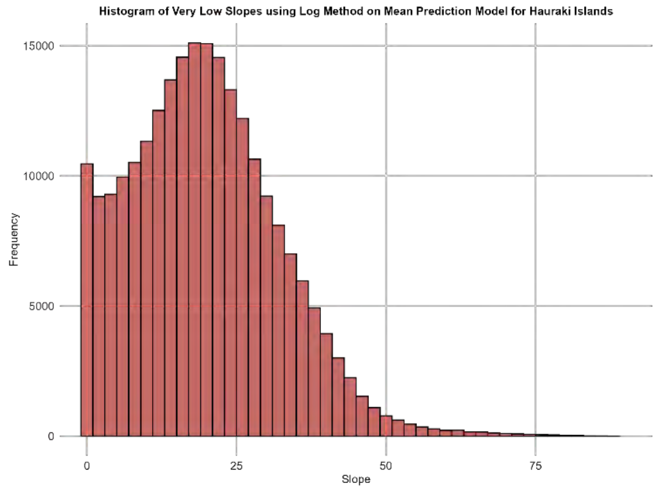


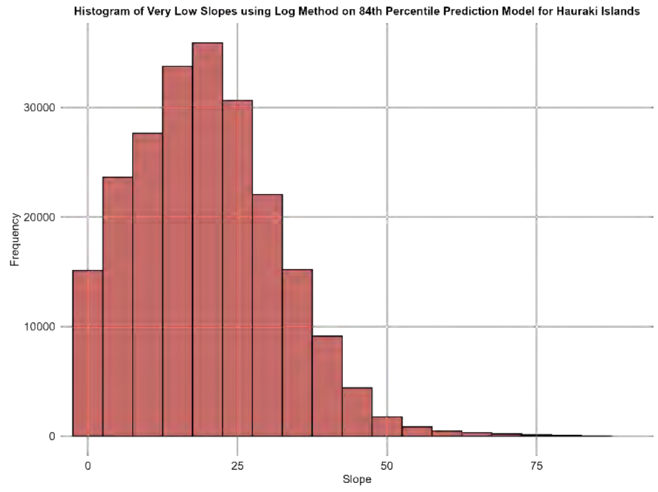


Mean predictions

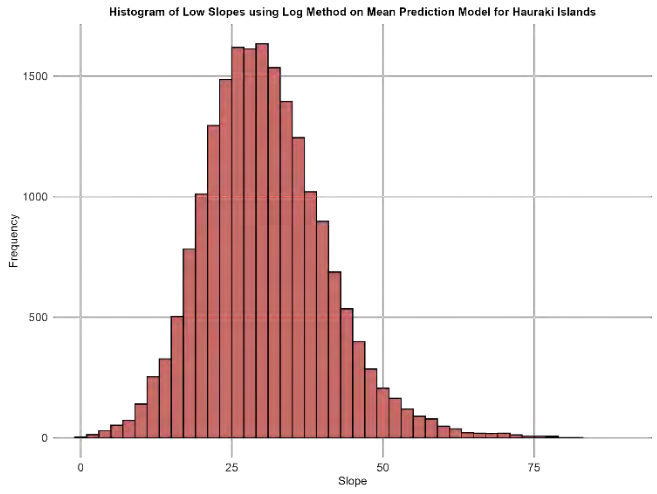
84th percentile predictions

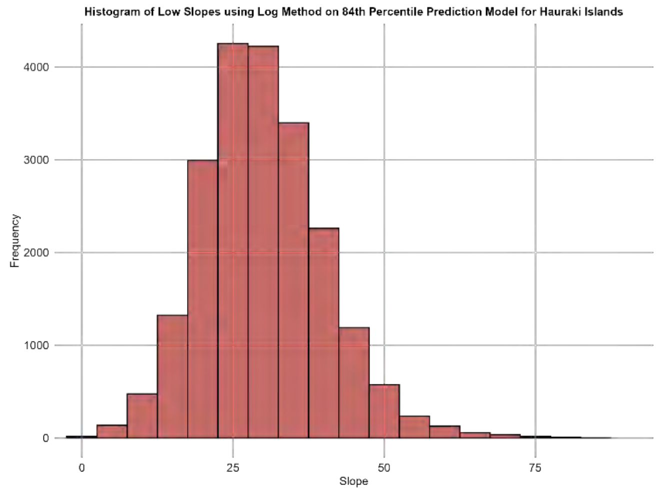
Very Low



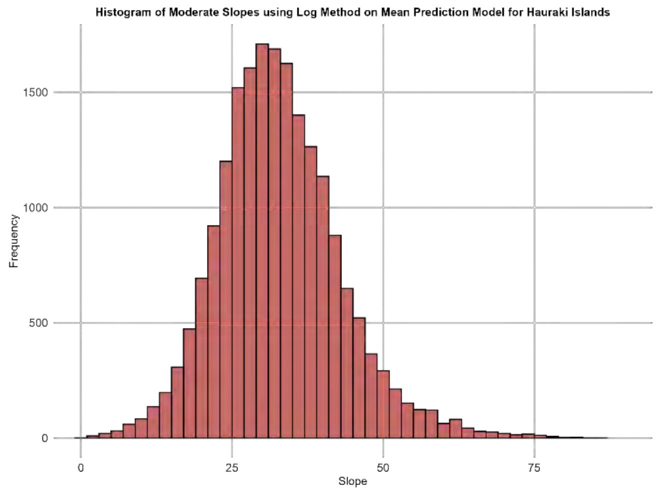


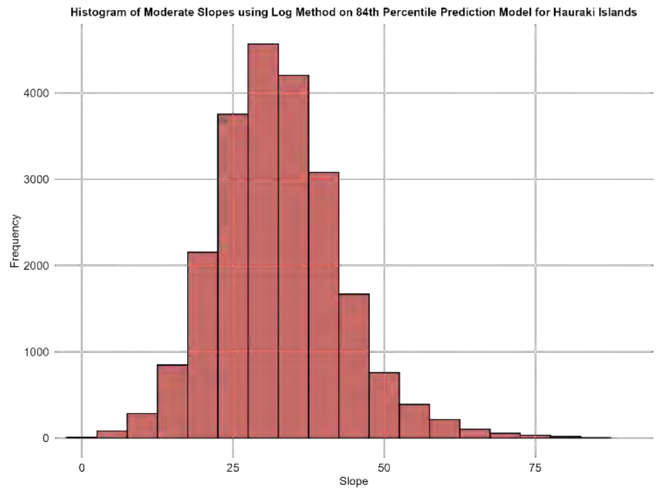
Low



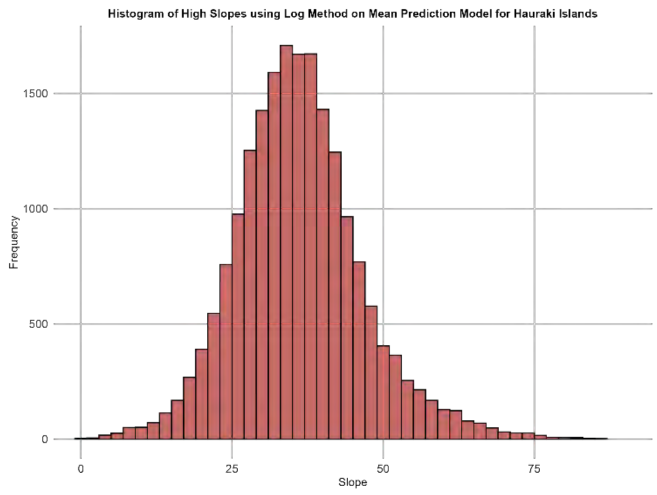


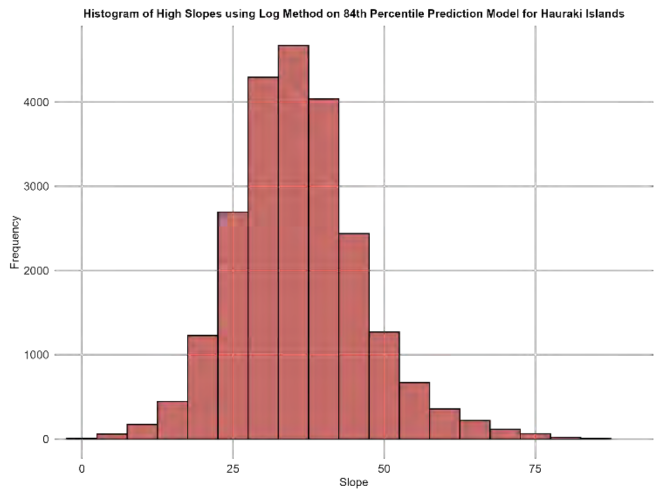
Moderate



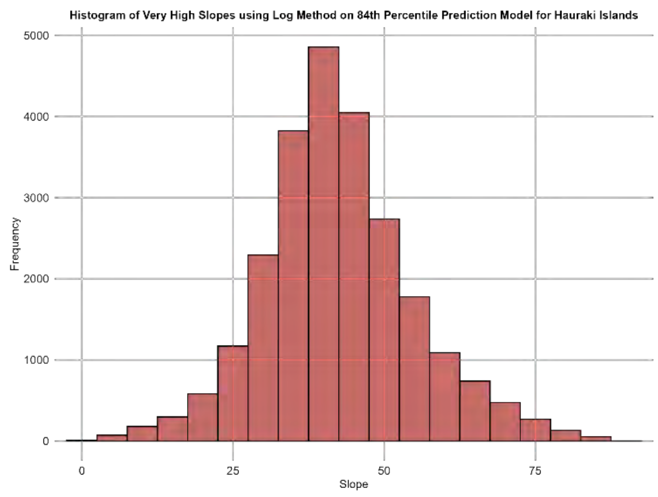


High





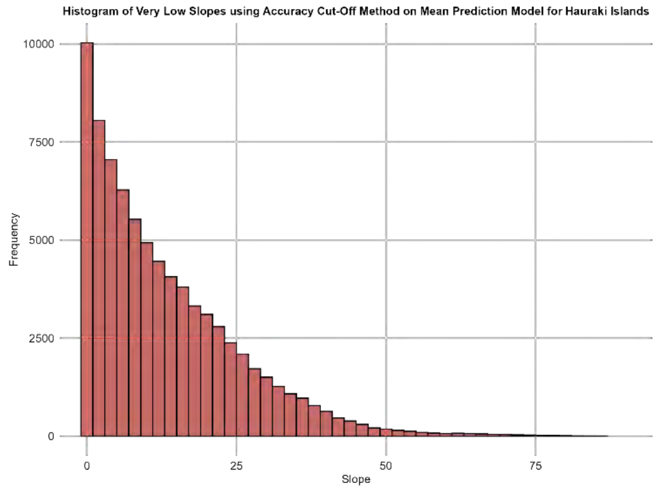
Very High

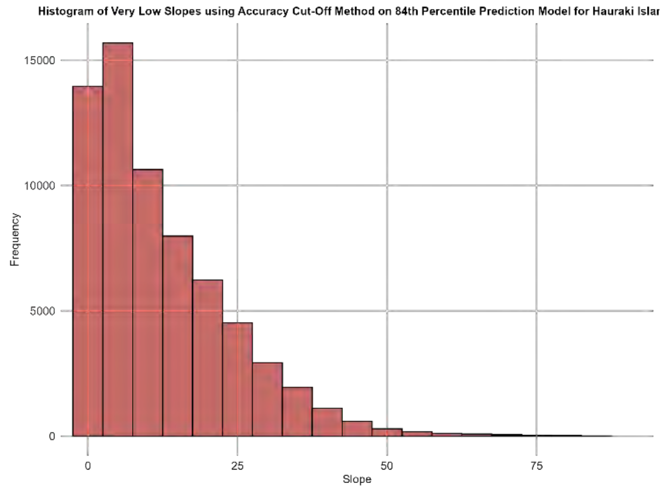


METHOD 3 (ACCURACY CUT-OFF)

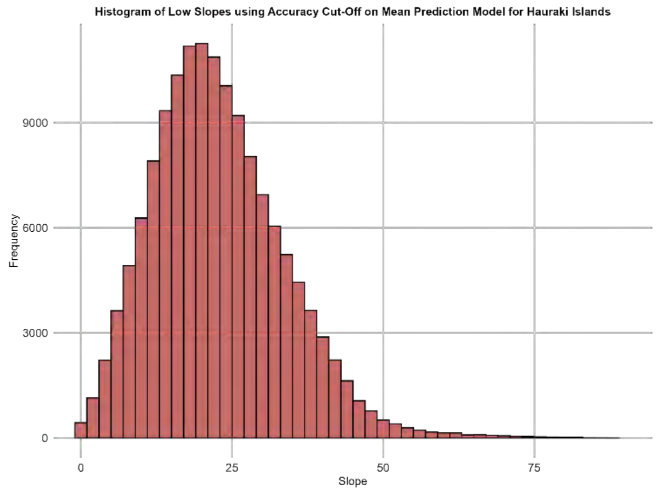
Mean predictions | 84th percentile predictions

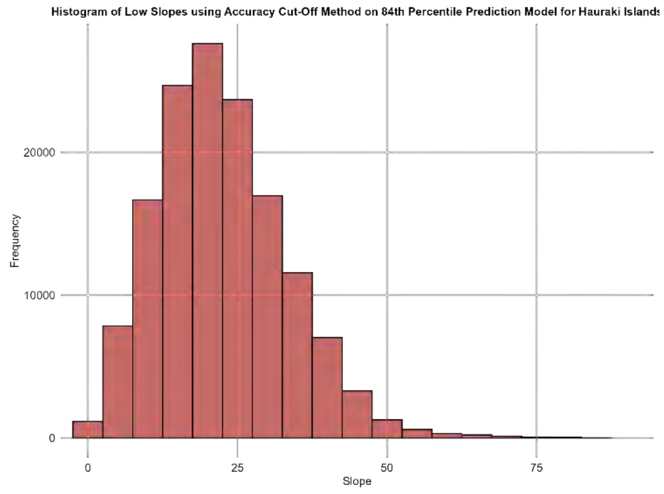
Very Low



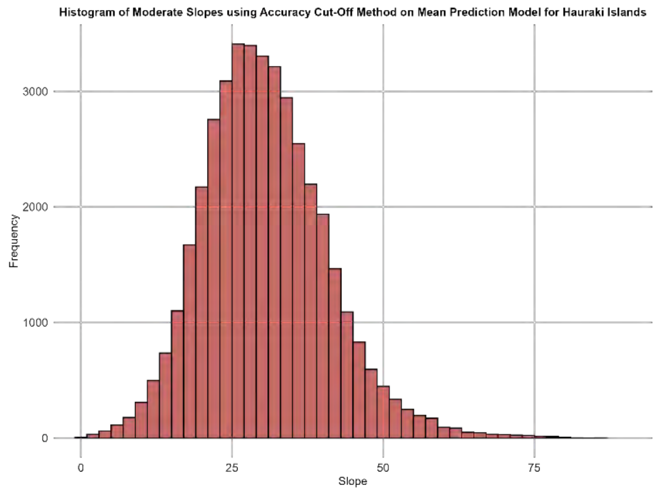


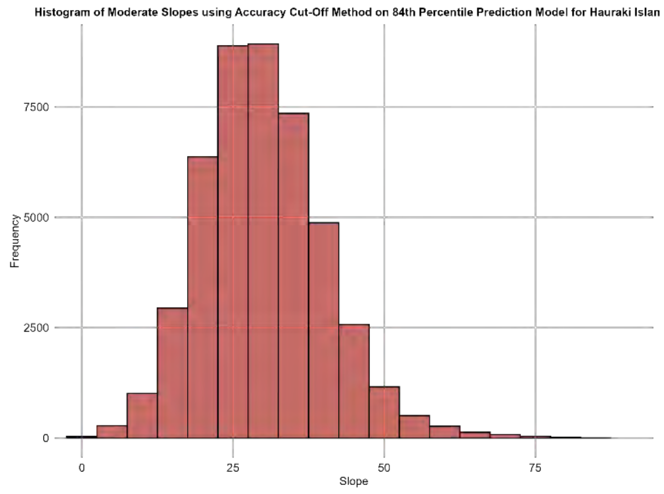
Low



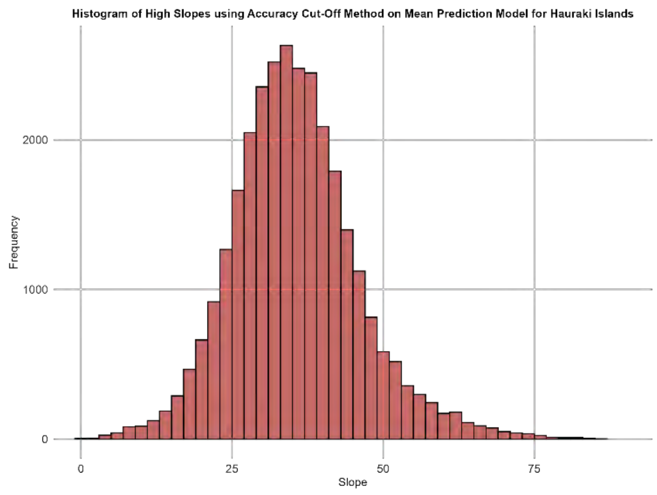


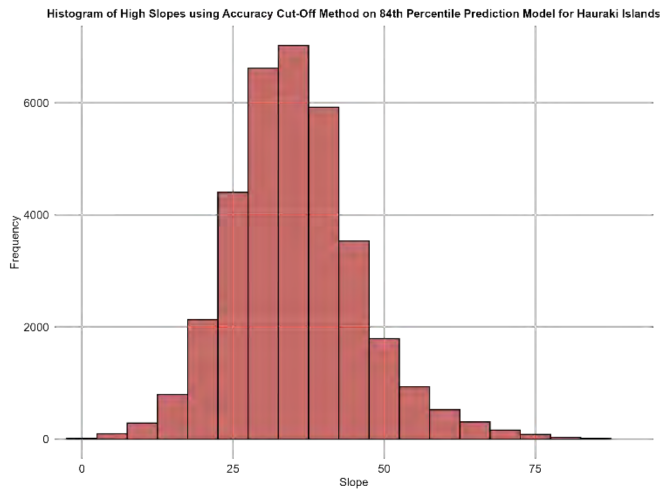
Moderate



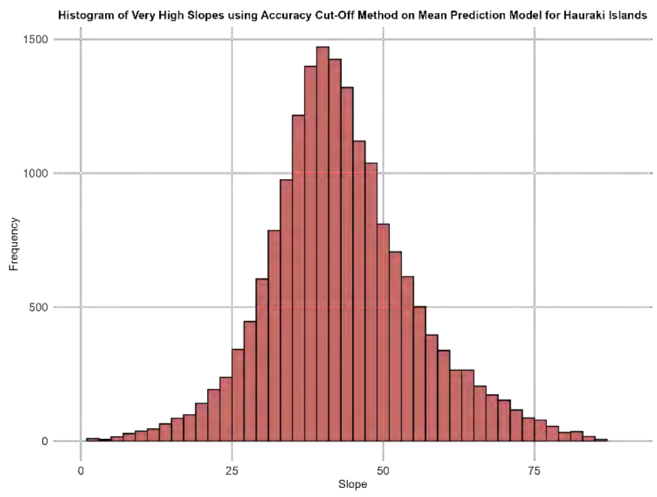


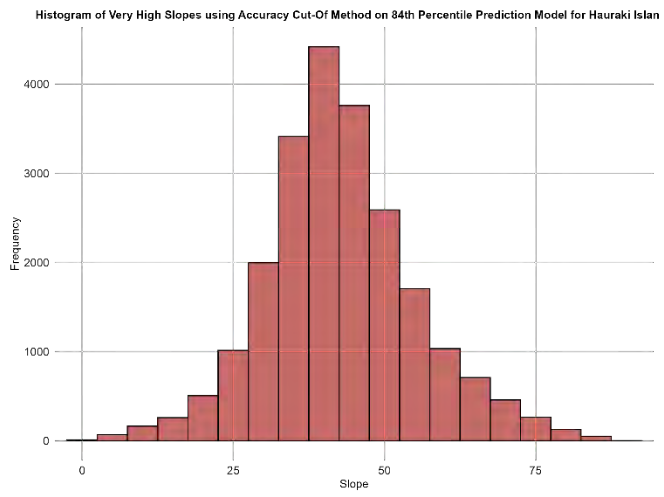
High





Very High



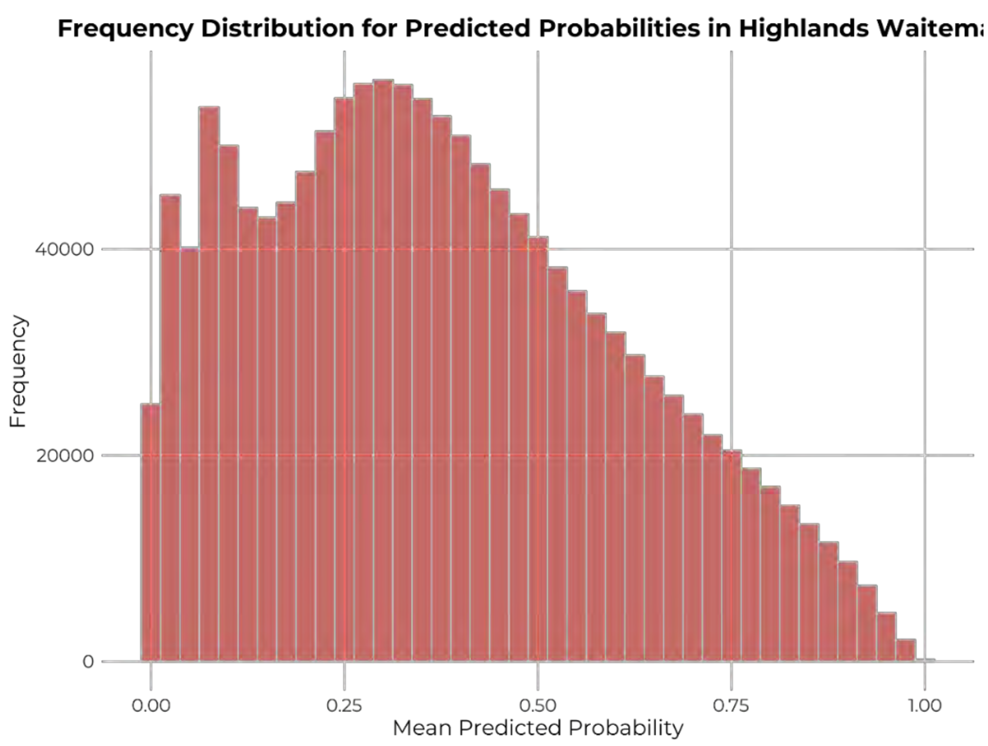


HIGHLANDS WAITEMATA

MODEL COEFFICIENTS

Variable	Mean Coefficient	Standard Error	95% Confidence Interval	
			Upper Bound	Lower Bound
Intercept	-2.71997	0.007157	-2.70593	-2.734
Aspect	-0.05563	0.00016	-0.05532	-0.05594
Curvature	-0.04006	0.000179	-0.03971	-0.04041
GeolUnit3	-0.13851	0.003769	-0.13112	-0.1459
GeolUnit4	-0.074	0.00225	-0.06959	-0.07842
GeolUnit5	-0.45202	0.036498	-0.38047	-0.52357
GeolUnit6	-0.14489	0.005528	-0.13406	-0.15573
GeolUnit7	1.382927	0.003528	1.389843	1.37601
GeolUnit8	1.036691	0.002125	1.040857	1.032525
GeolUnit9	-0.27842	0.002831	-0.27287	-0.28397
GeolUnit14	-8.77638	0.019942	-8.73728	-8.81548
Geomorphon2	1.127607	0.006346	1.140048	1.115166
Geomorphon3	1.245337	0.006256	1.257601	1.233073
Geomorphon4	1.295295	0.007148	1.309307	1.281283
Geomorphon5	1.393194	0.00625	1.405448	1.38094
Geomorphon6	1.716271	0.006234	1.728493	1.70405
Geomorphon7	1.975813	0.006251	1.988068	1.963558
Geomorphon8	0.837036	0.006584	0.849943	0.824129
Geomorphon9	2.099307	0.006225	2.111511	2.087102
Geomorphon10	2.621307	0.006329	2.633714	2.608901
DistanceToStream10	-0.11874	0.001716	-0.11537	-0.1221
DistanceToStream20	-0.01545	0.001457	-0.0126	-0.01831
DistanceToStream9999	-0.22287	0.001286	-0.22035	-0.22539
LCDB1	-1.07939	0.002337	-1.07481	-1.08397
LCDB2	-0.99662	0.002662	-0.9914	-1.00184
LCDB3	-0.39074	0.002897	-0.38506	-0.39642
LCDB4	0.12277	0.00232	0.127319	0.118221
LCDB5	0.150423	0.005721	0.161639	0.139206
LCDB7	-1.20309	0.003406	-1.19642	-1.20977
LocalSlopeRelief	0.653323	0.000282	0.653876	0.652771
Slope	0.719087	0.000216	0.71951	0.718665
OLFP10	-0.07615	0.00069	-0.0748	-0.0775
OLFP9999	0.118333	0.000524	0.119361	0.117305
GeolUnit11	-8.69623	0.133336	-8.42606	-8.96639
GeolUnit12	-8.69919	0.116191	-8.46652	-8.93186

PROBABILITY DISTRIBUTION



AREA COMPARISONS

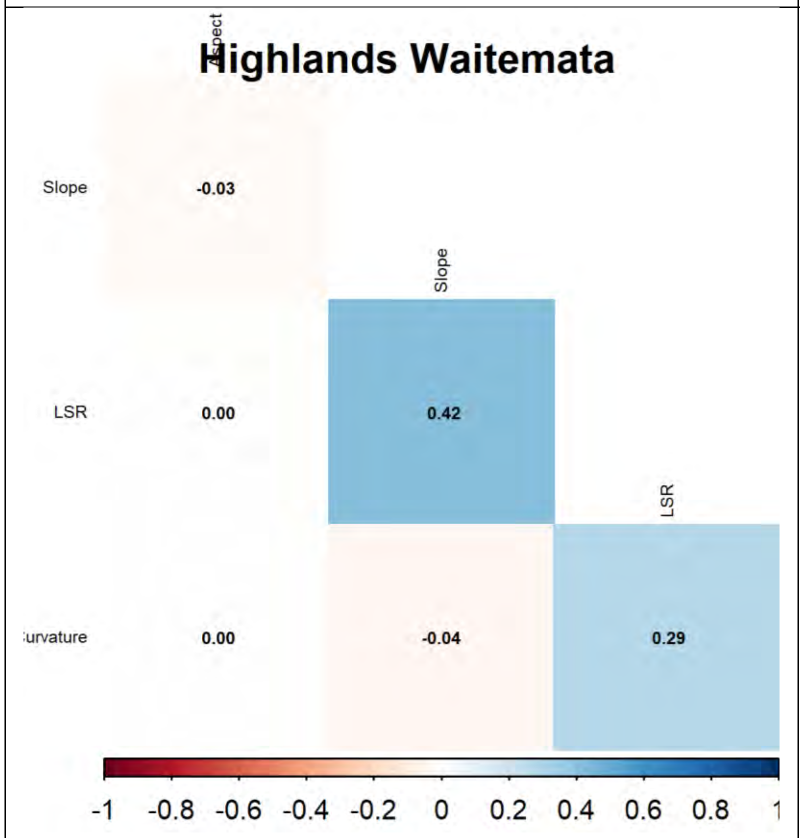
	Land area comparison					
	Highlands Waitemata					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	16.3%	15.4%	75.0%	73.9%	31.8%	30.5%
Low	32.4%	31.7%	6.2%	6.4%	39.1%	39.2%
Moderate	38.9%	39.7%	6.3%	6.5%	11.5%	11.9%
High	12.4%	13.2%	6.2%	6.5%	10.0%	10.4%
Very High			6.3%	6.7%	7.6%	8.1%

	Landslide inventory density (landslide area per class/total landslide area per region)					
	Highlands Waitemata					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	1.0%	0.9%	28.8%	27.4%	4.5%	4.1%
Low	9.0%	8.4%	8.7%	8.5%	20.0%	19.0%
Moderate	40.0%	39.0%	12.4%	12.1%	14.8%	14.7%
High	50.0%	51.8%	18.5%	18.7%	24.5%	24.2%
Very High			31.6%	33.2%	36.2%	38.0%

	Landslide number density (landslide cells/total cells per region)					
	Highlands Waitemata					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	0.1%	0.1%	0.4%	0.4%	0.2%	0.1%
Low	0.3%	0.3%	1.6%	1.5%	0.6%	0.5%
Moderate	1.1%	1.1%	2.2%	2.1%	1.4%	1.4%
High	4.5%	4.4%	3.3%	3.2%	2.7%	2.6%
Very High			5.6%	5.6%	5.3%	5.2%

VARIABLE CORRELATIONS

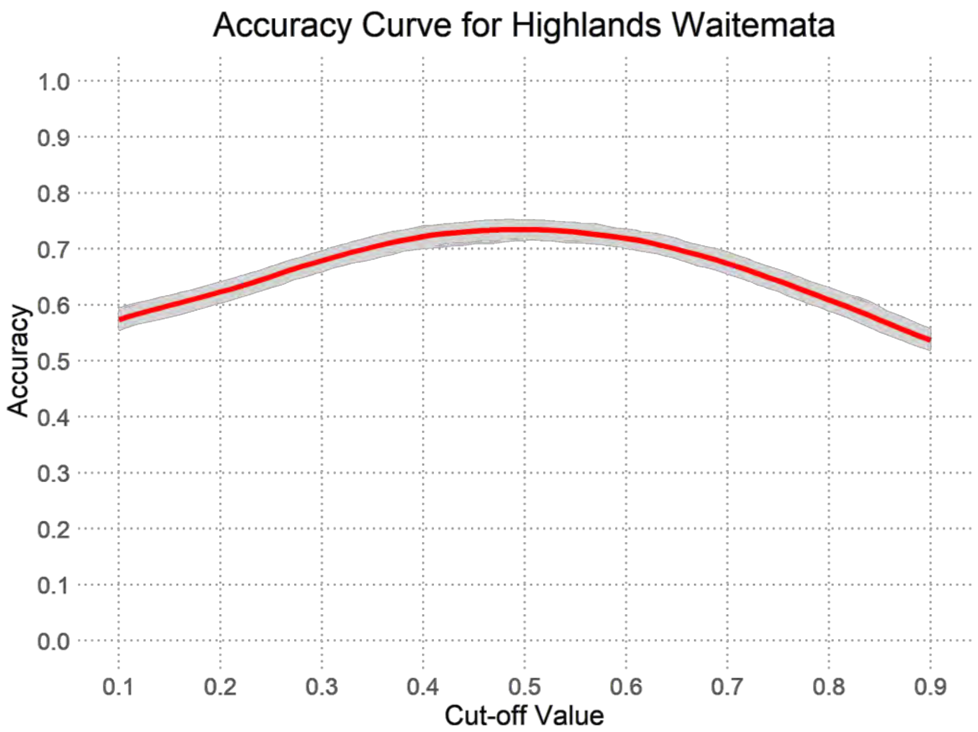
Continuous Variables



Categorical Variables

GeolUnit_vs_Geomorphon	0.158730791
GeolUnit_vs_DistanceToStream	0.049347421
GeolUnit_vs_LCDB	0.133453165
GeolUnit_vs_OLFP	0.060940350
Geomorphon_vs_DistanceToStream	0.245583632
Geomorphon_vs_LCDB	0.158055143
Geomorphon_vs_OLFP	0.255590477
DistanceToStream_vs_LCDB	0.049120966
DistanceToStream_vs_OLFP	0.141008302
LCDB_vs_OLFP	0.034227612

ACCURACY PLOT



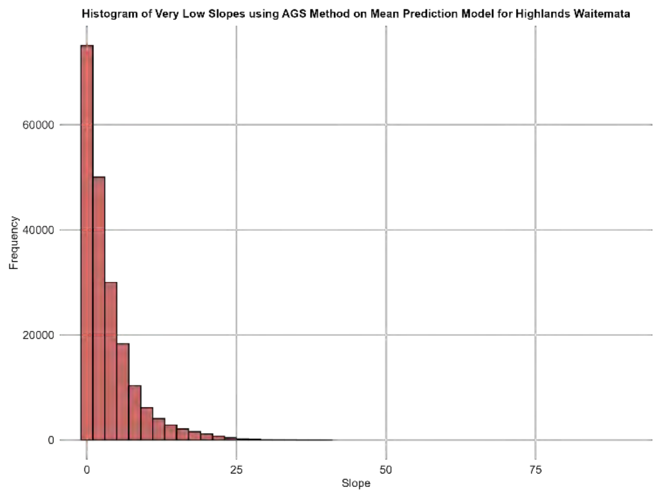
SLOPE ANGLE DISTRIBUTIONS

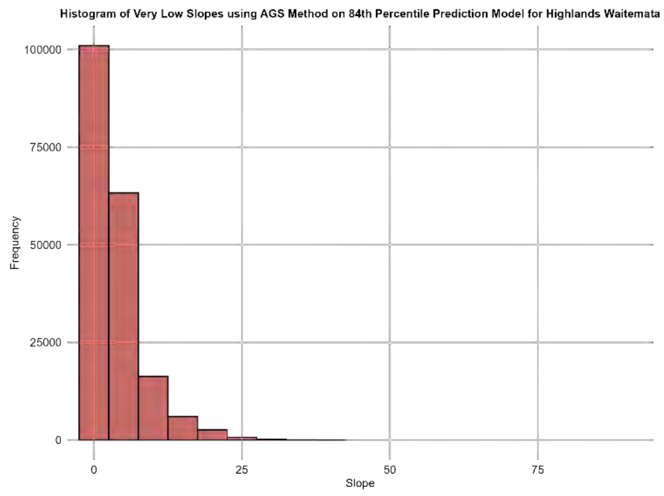
METHOD 1 (AGS)

Mean predictions

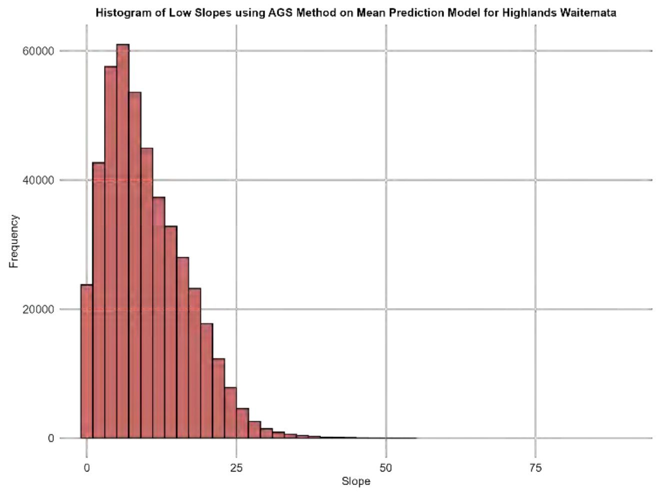
84^{th} percentile predictions

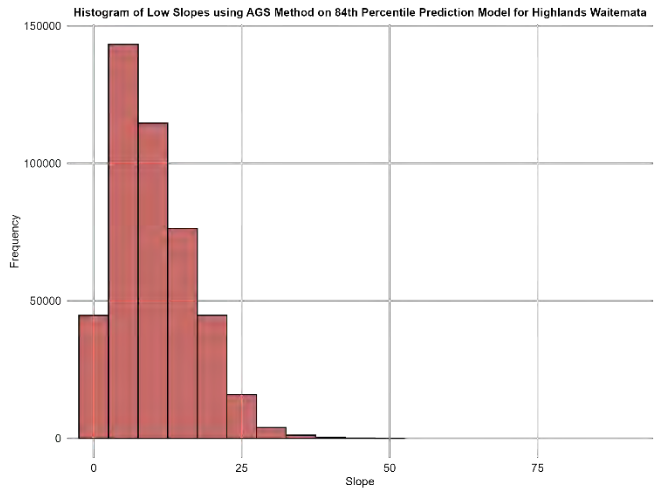
Very Low



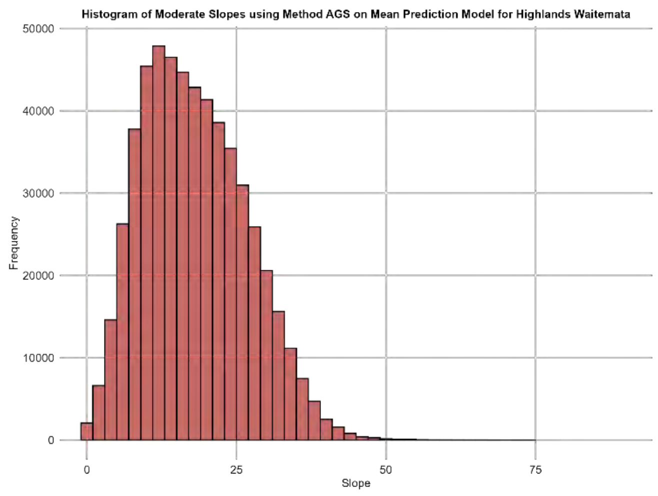


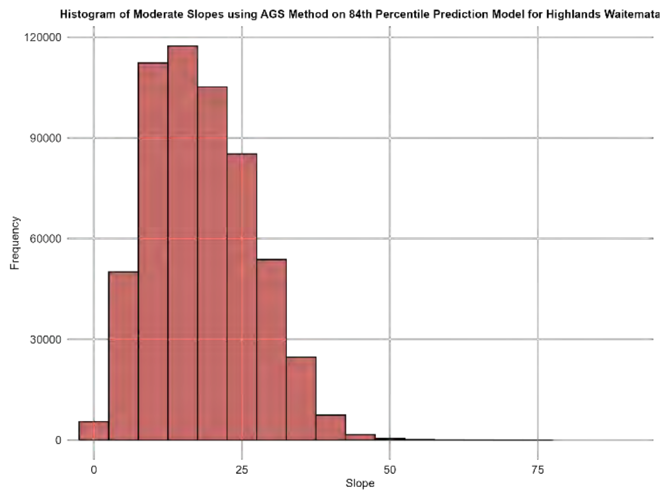
Low



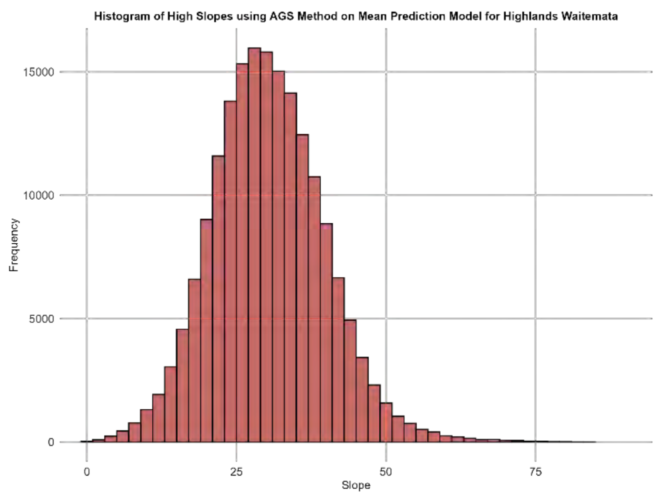


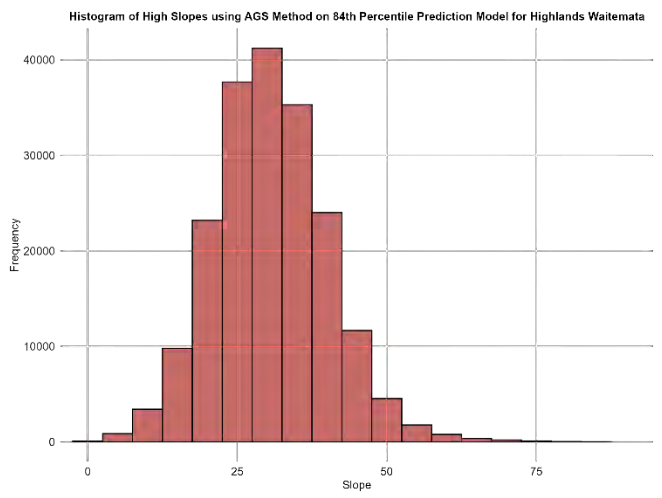
Moderate





High

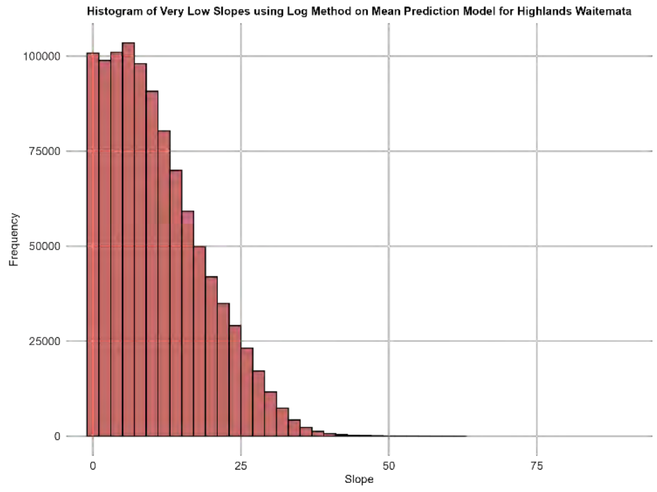


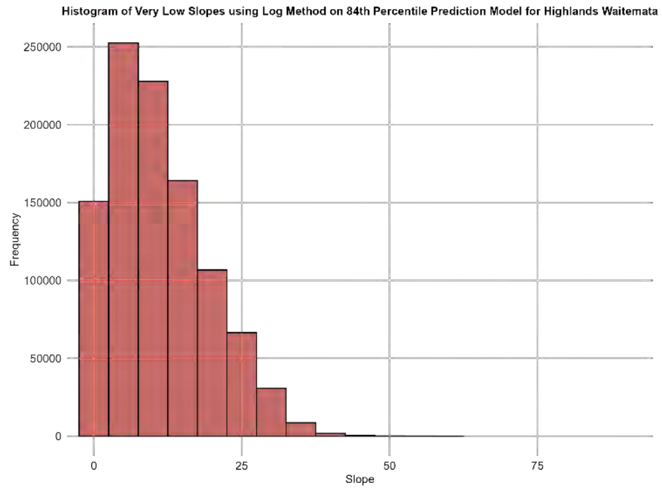


METHOD 2 (LOG BINS)

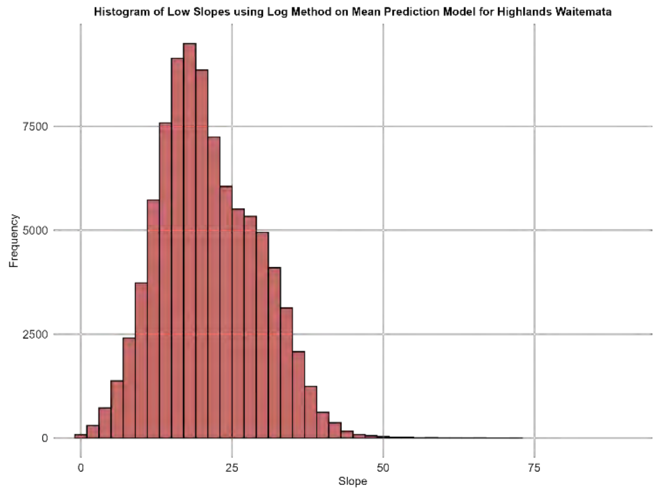
Mean predictions | 84^{th} percentile predictions

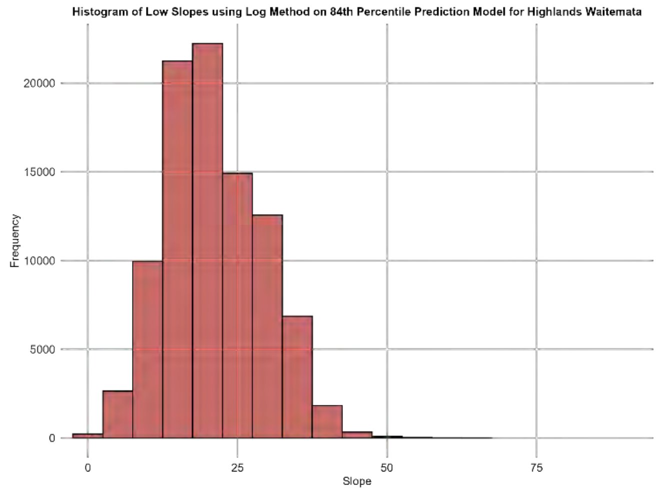
Very Low



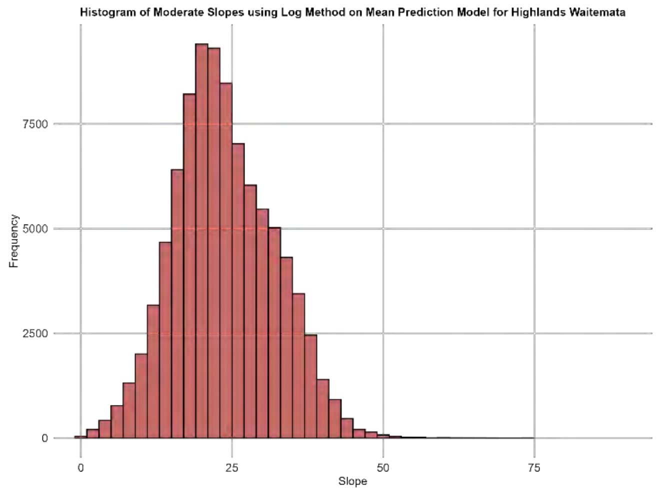


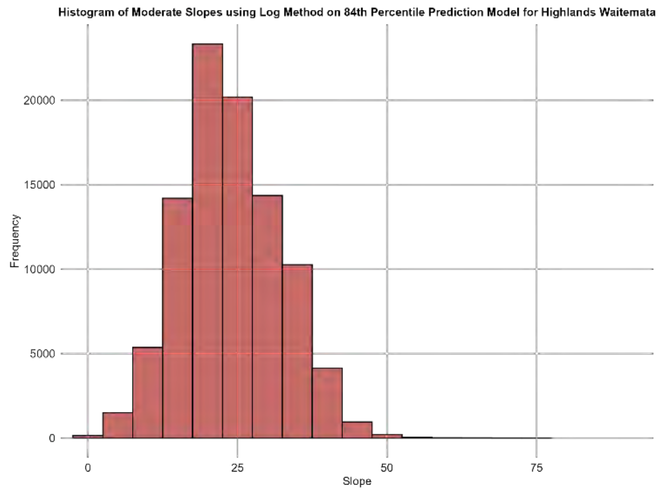
Low



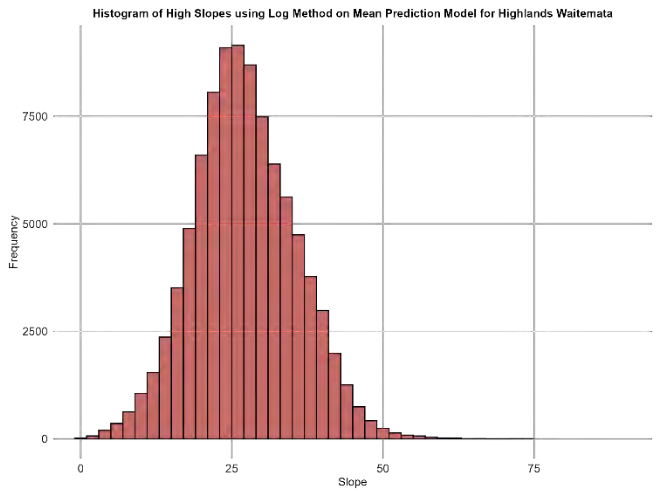


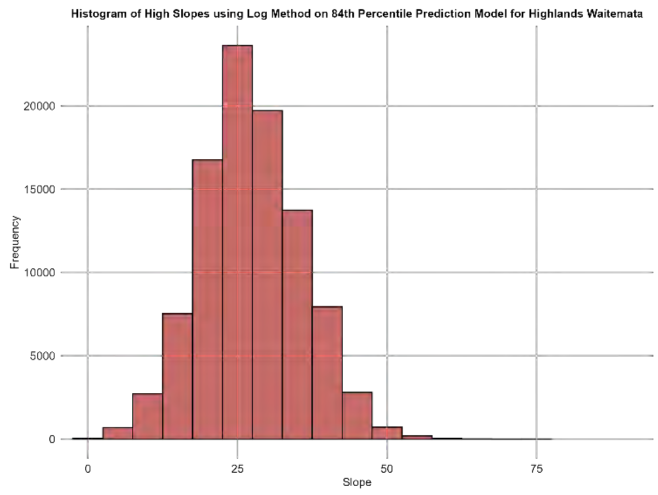
Moderate



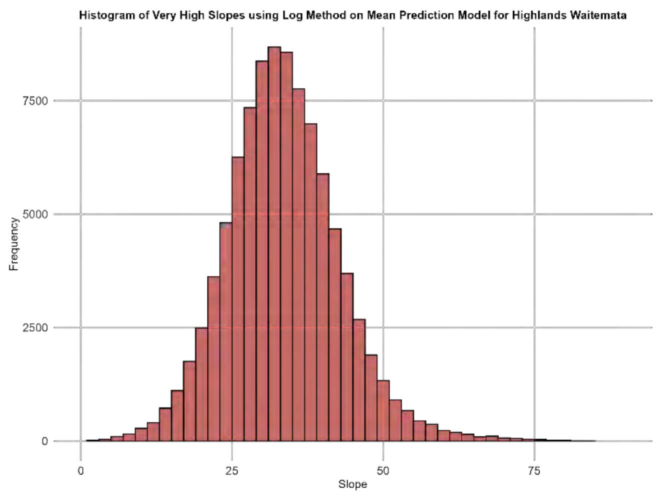


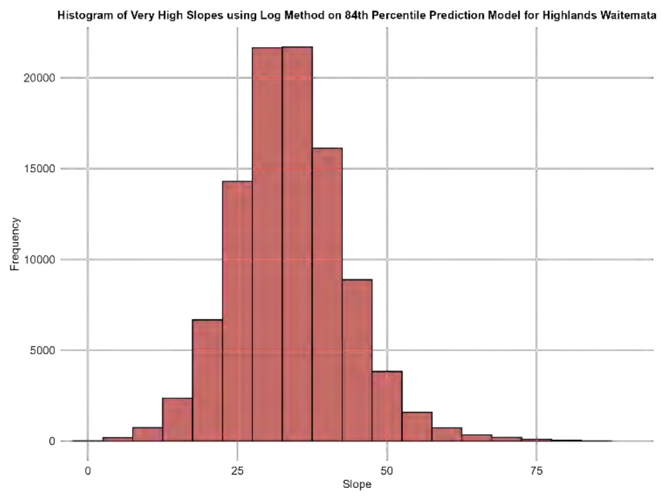
High





Very High



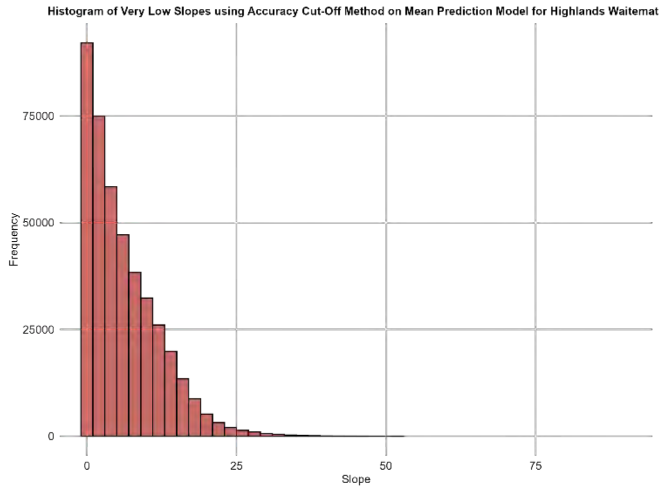


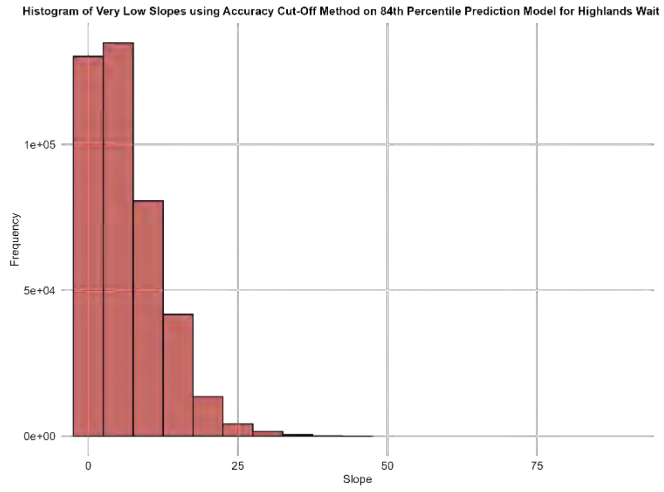
METHOD 3 (ACCURACY CUT-OFF)

Mean predictions

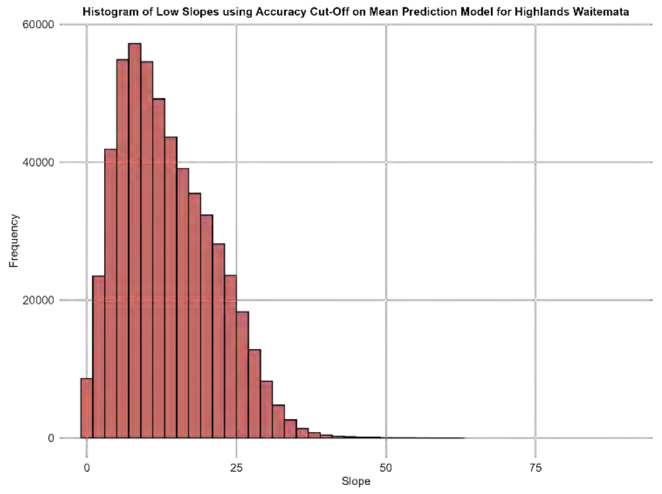
84th percentile predictions

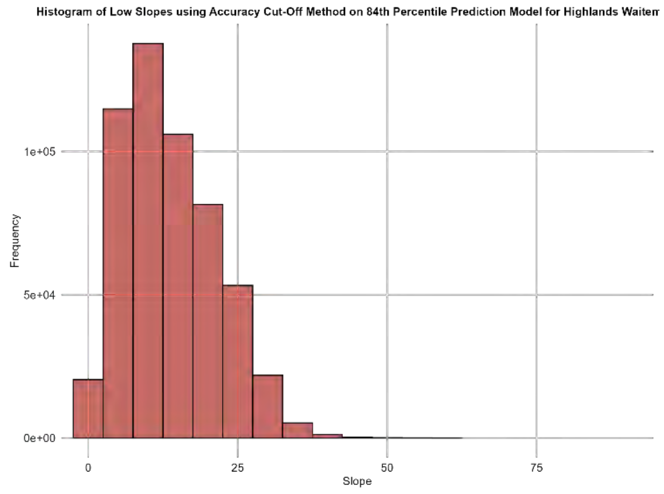
Very Low



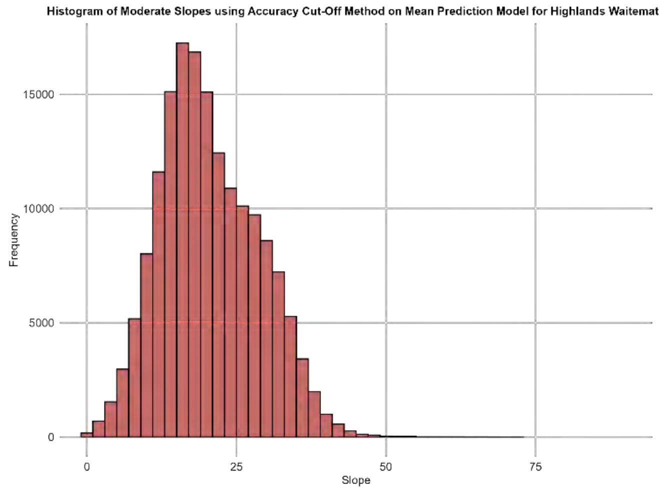


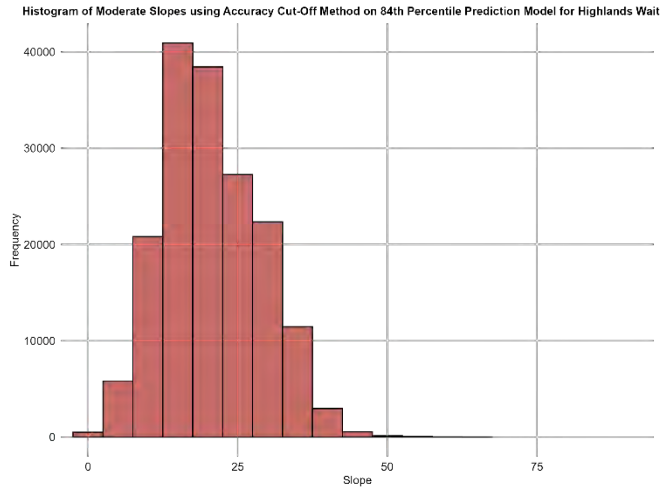
Low



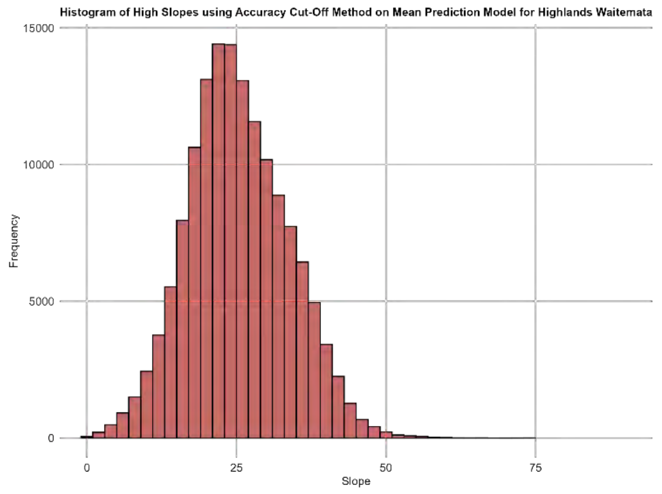


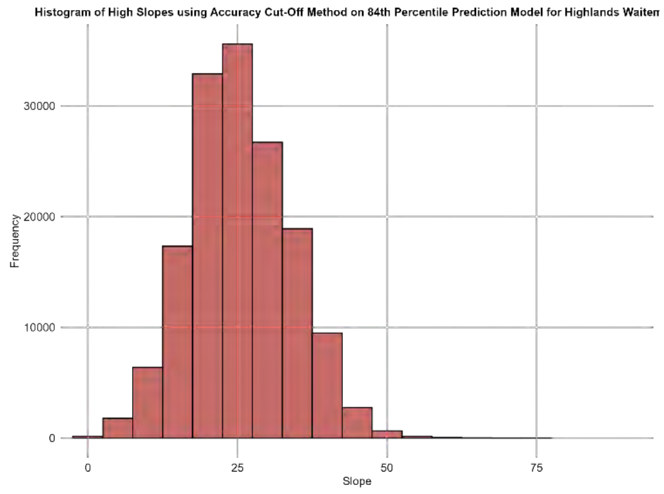
Moderate



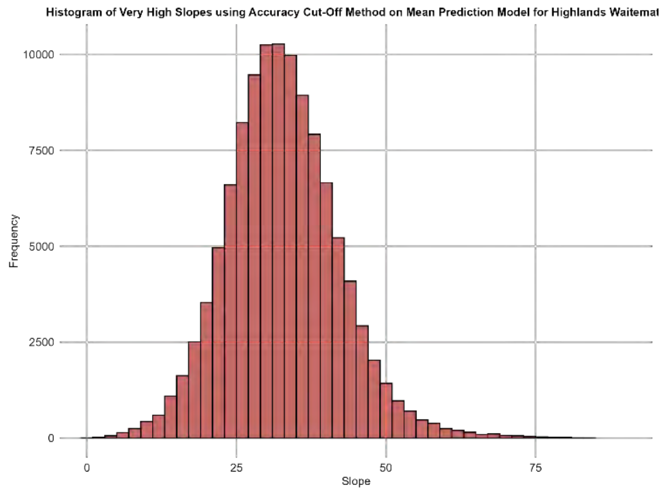


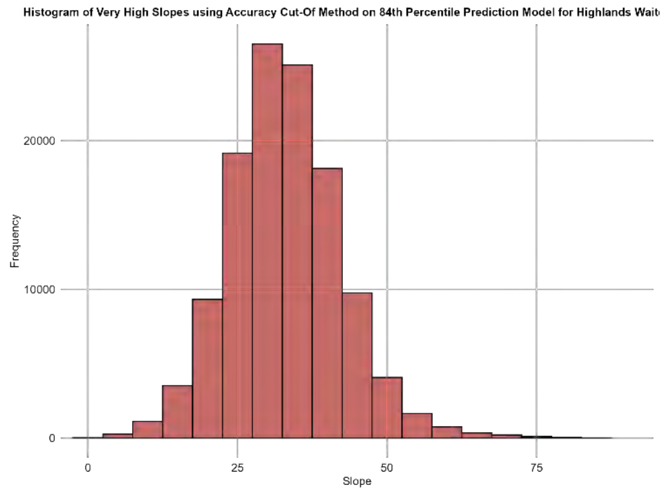
High





Very High



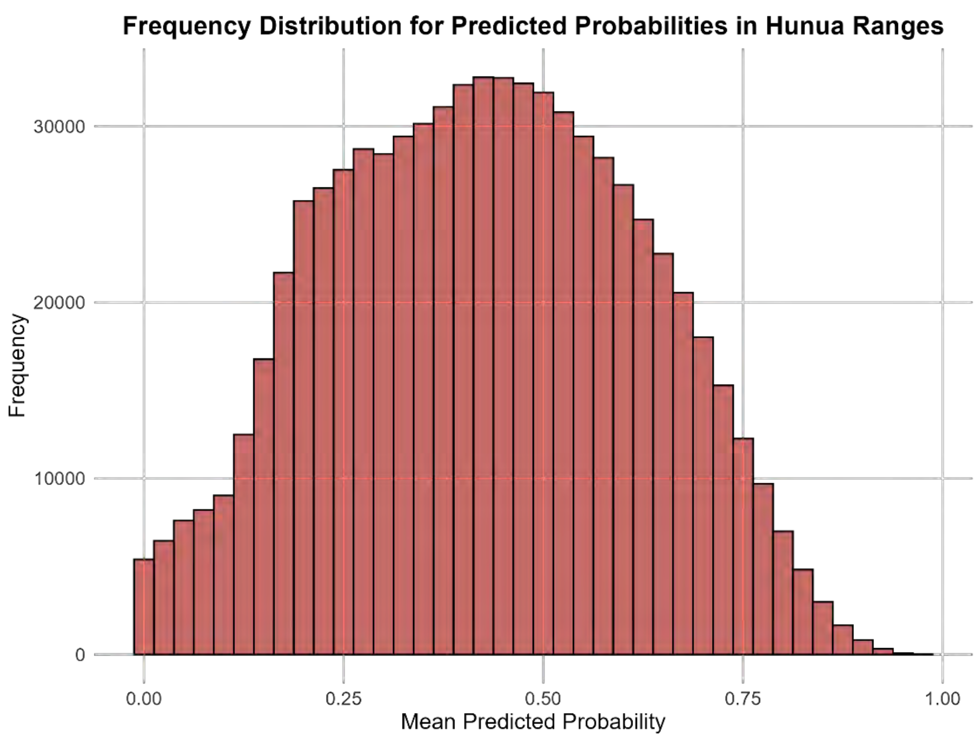


HUNUA RANGES

MODEL COEFFICIENTS

Variable	Mean Coefficient	Standard Error	95% Confidence Interval	
			Upper Bound	Lower Bound
Intercept	-14.0262	0.0077	-14.0112	-14.0413
OLFP10	0.0040	0.0011	0.0062	0.0018
OLFP9999	0.0203	0.0009	0.0220	0.0185
LocalSlopeRelief	0.3497	0.0003	0.3503	0.3491
GeolUnit4	-0.7057	0.0006	-0.7045	-0.7070
GeolUnit6	-1.1206	0.0013	-1.1180	-1.1232
GeolUnit8	-1.4557	0.0022	-1.4514	-1.4599
GeolUnit10	-13.9528	0.0103	-13.9326	-13.9730
GeolUnit11	-3.5044	0.1016	-3.3052	-3.7037
GeolUnit12	-4.7605	0.0755	-4.6124	-4.9086
GeolUnit13	-2.0397	0.0220	-1.9965	-2.0829
GeolUnit14	-0.6983	0.0017	-0.6949	-0.7017
Curvature	-0.0823	0.0002	-0.0818	-0.0828
LCDB1	0.5171	0.0025	0.5221	0.5121
LCDB2	0.2701	0.0034	0.2768	0.2634
LCDB3	0.7920	0.0030	0.7979	0.7862
LCDB4	1.6433	0.0025	1.6482	1.6383
LCDB5	-0.1312	0.0047	-0.1220	-0.1405
LCDB7	-0.3766	0.0042	-0.3683	-0.3849
Aspect	-0.1547	0.0002	-0.1544	-0.1550
DistanceToStream10	0.0138	0.0019	0.0175	0.0101
DistanceToStream20	-0.1218	0.0017	-0.1186	-0.1251
DistanceToStream9999	0.4256	0.0014	0.4284	0.4228
Slope	0.6013	0.0003	0.6018	0.6008
Geomorphon2	12.0647	0.0073	12.0789	12.0505
Geomorphon3	12.0849	0.0072	12.0990	12.0708
Geomorphon4	10.8597	0.0134	10.8859	10.8335
Geomorphon5	12.2194	0.0072	12.2334	12.2053
Geomorphon6	12.5843	0.0072	12.5984	12.5703
Geomorphon7	12.7712	0.0072	12.7853	12.7571
Geomorphon8	9.8307	0.0190	9.8680	9.7934
Geomorphon9	12.7591	0.0072	12.7732	12.7450
Geomorphon10	13.0678	0.0073	13.0820	13.0535

PROBABILITY DISTRIBUTION



AREA COMPARISONS

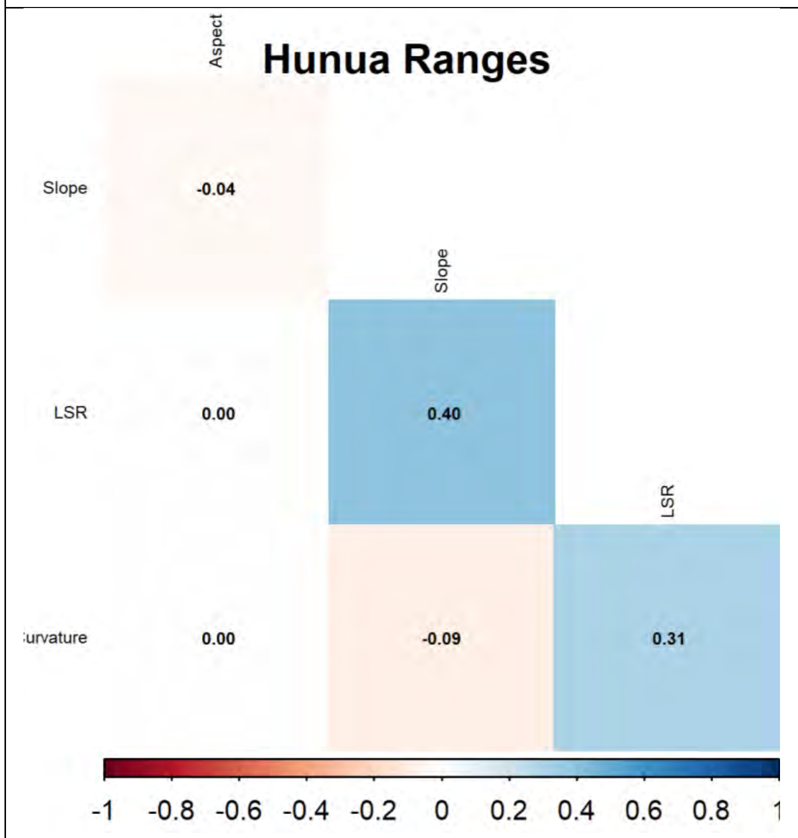
	Land area comparison					
	Hunua Ranges					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	9.2%	8.2%	75.0%	73.2%	18.3%	16.7%
Low	26.7%	25.7%	6.2%	6.4%	47.0%	46.6%
Moderate	43.7%	44.0%	6.2%	6.5%	15.2%	15.6%
High	20.5%	22.1%	6.3%	6.7%	13.1%	13.9%
Very High			6.2%	7.1%	6.4%	7.2%

	Landslide inventory density (landslide area per class/total landslide area per region)					
	Hunua Ranges					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	1.0%	0.9%	43.5%	41.0%	3.2%	2.8%
Low	9.0%	8.0%	9.4%	9.3%	28.7%	27.1%
Moderate	40.0%	38.4%	11.2%	11.5%	19.6%	19.0%
High	50.0%	52.7%	13.9%	14.1%	25.9%	26.6%
Very High			22.0%	24.1%	22.5%	24.5%

	Landslide number density (landslide cells/total cells per region)					
	Hunua Ranges					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	0.2%	0.2%	1.0%	0.9%	0.3%	0.3%
Low	0.6%	0.5%	2.5%	2.4%	1.0%	1.0%
Moderate	1.5%	1.4%	3.0%	2.9%	2.1%	2.0%
High	4.0%	4.0%	3.7%	3.5%	3.3%	3.2%
Very High			5.8%	5.6%	5.8%	5.6%

VARIABLE CORRELATIONS

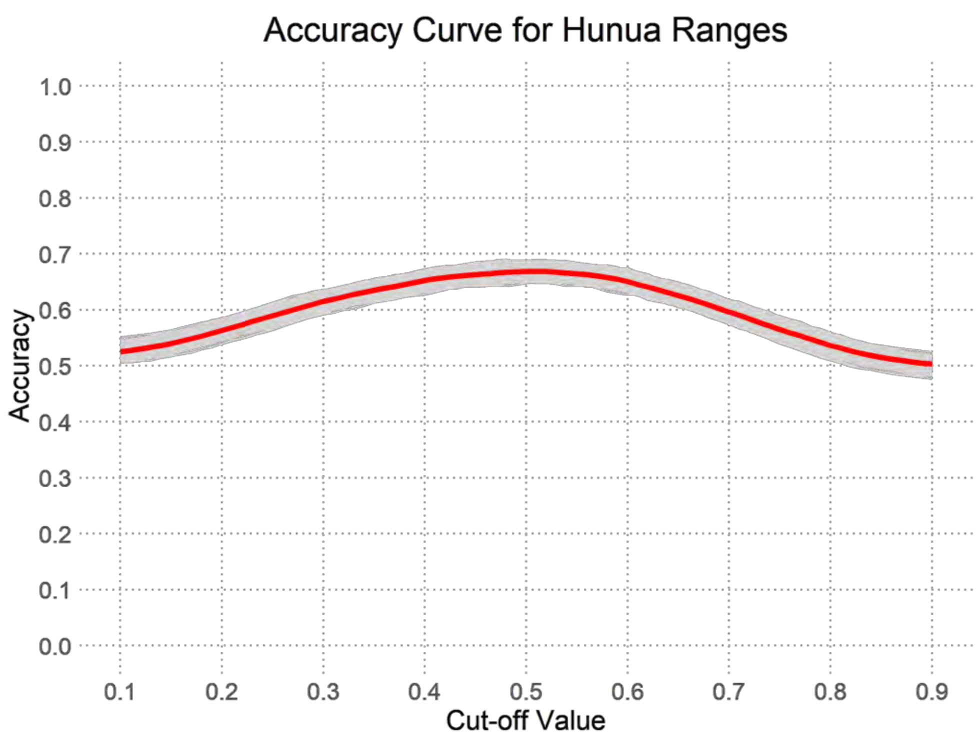
Continuous Variables



Categorical Variables

GeolUnit_vs_Geomorphon	0.093540962
GeolUnit_vs_DistanceToStream	0.038697042
GeolUnit_vs_LCDB	0.177387551
GeolUnit_vs_OLFP	0.054805954
Geomorphon_vs_DistanceToStream	0.277186890
Geomorphon_vs_LCDB	0.113591077
Geomorphon_vs_OLFP	0.327610131
DistanceToStream_vs_LCDB	0.037235373
DistanceToStream_vs_OLFP	0.219602989
LCDB_vs_OLFP	0.043008976

ACCURACY PLOT



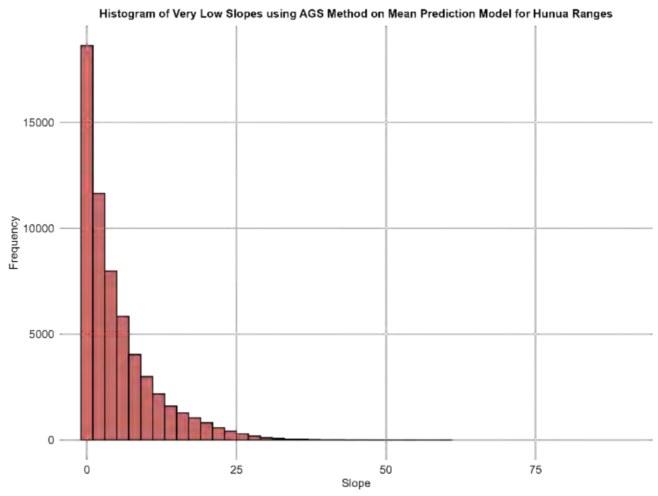
SLOPE ANGLE DISTRIBUTIONS

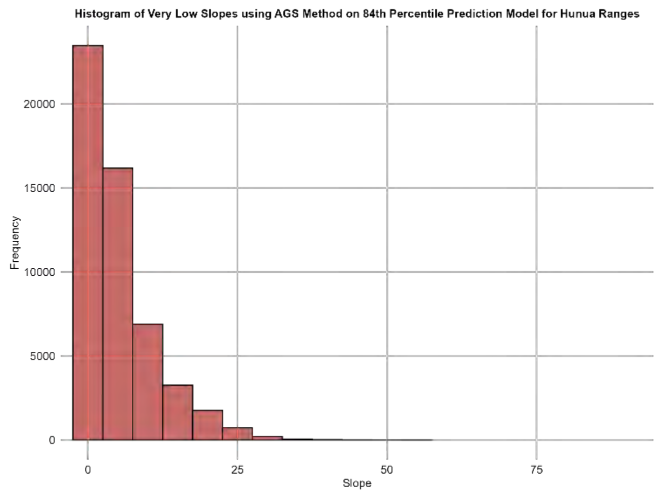
METHOD 1 (AGS)

Mean predictions

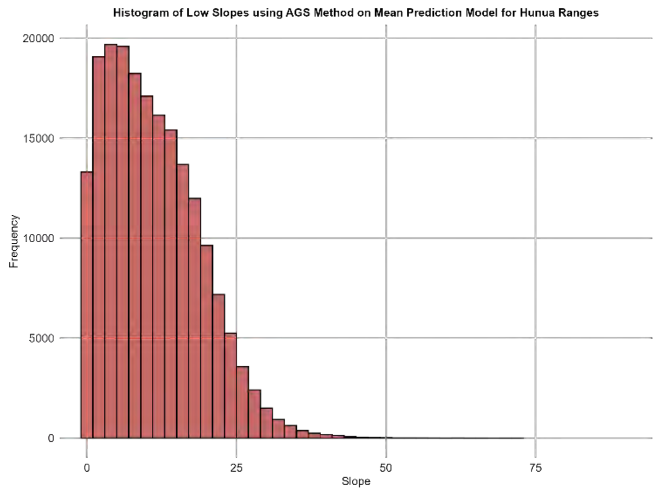
84th percentile predictions

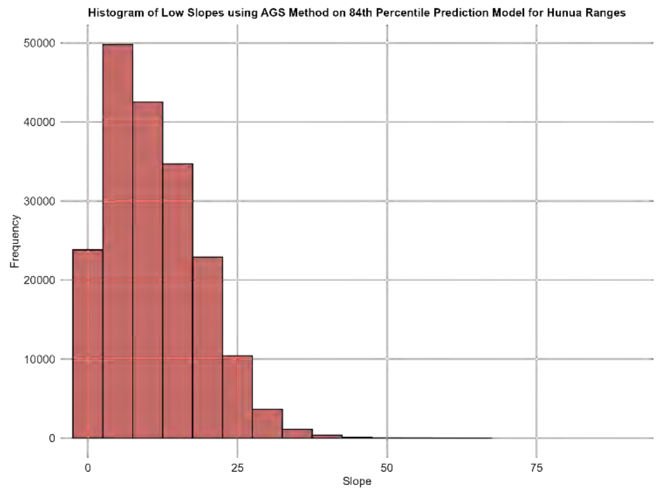
Very Low



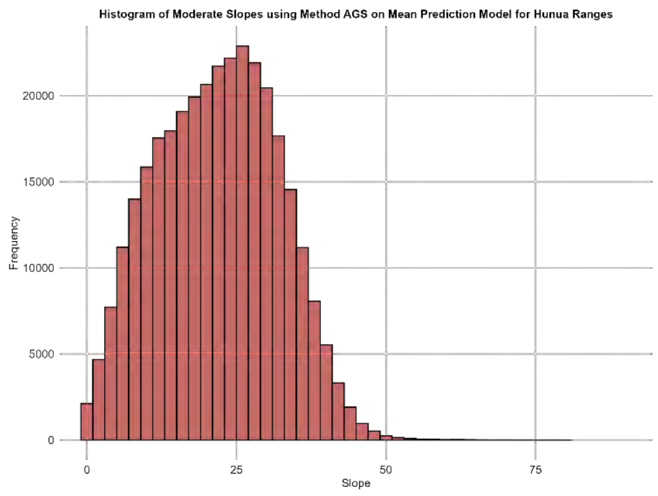


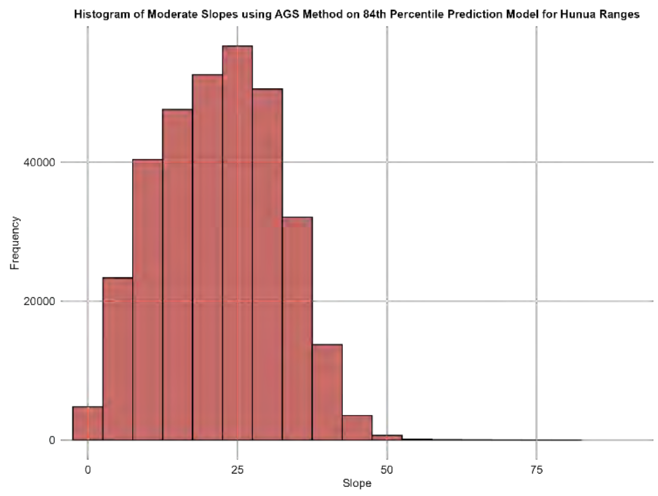
Low



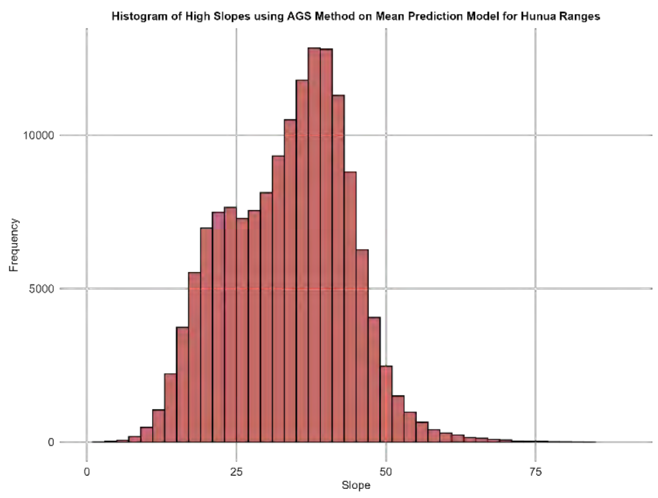


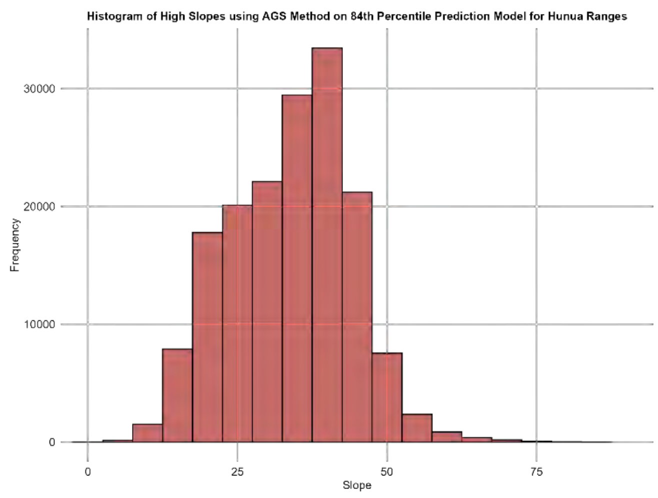
Moderate





High

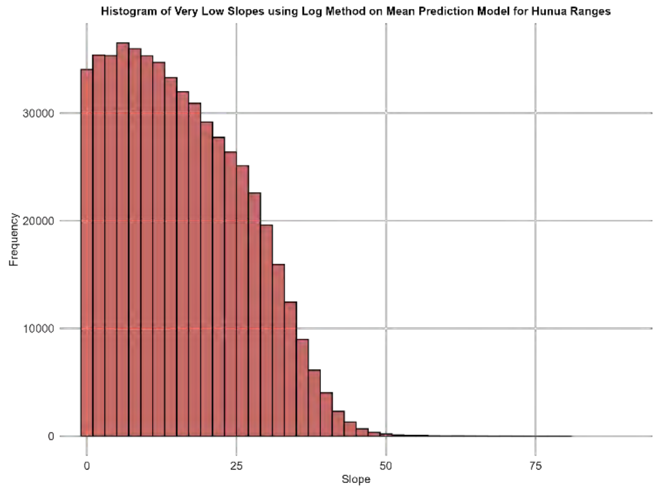


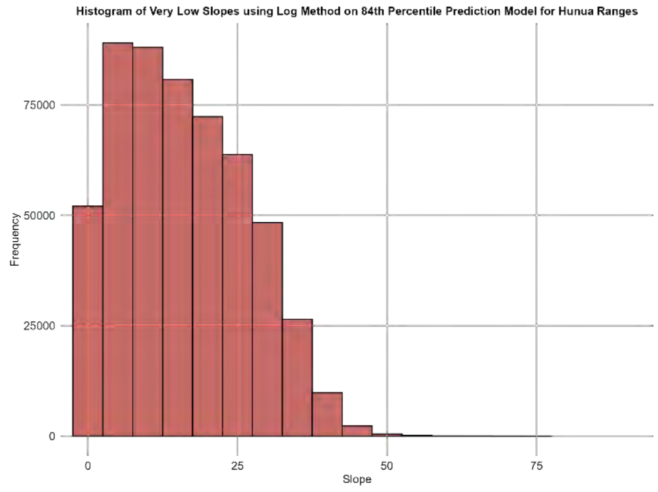


METHOD 2 (LOG BINS)

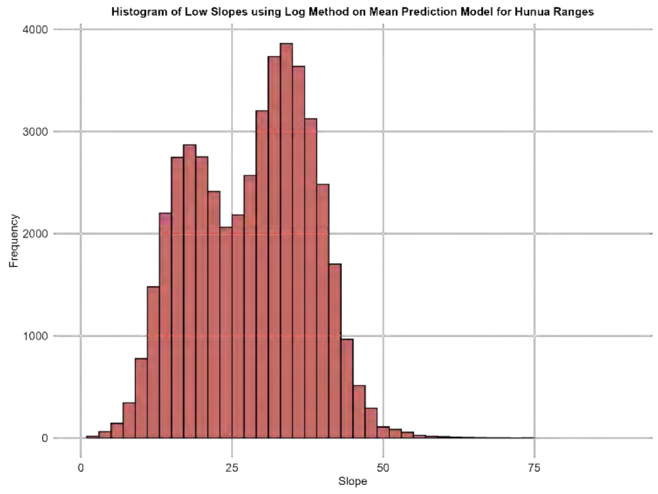
Mean predictions | 84th percentile predictions

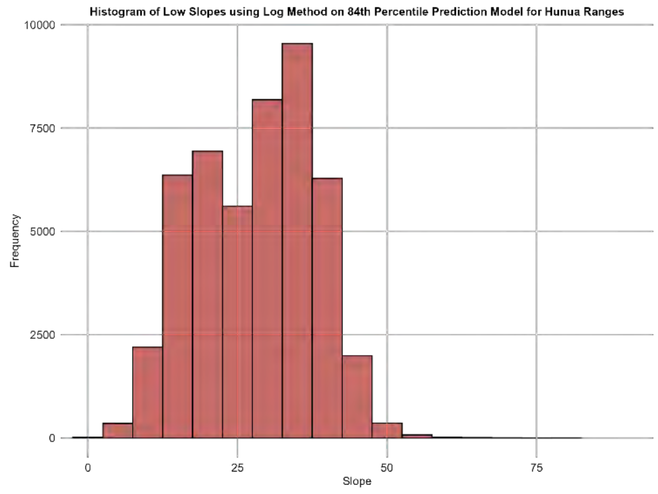
Very Low



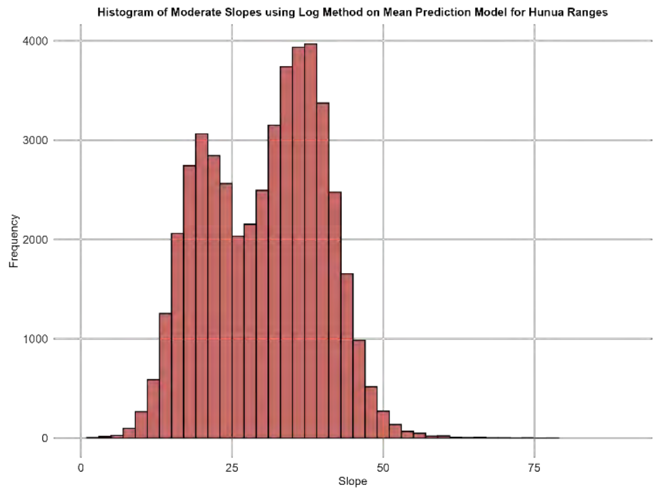


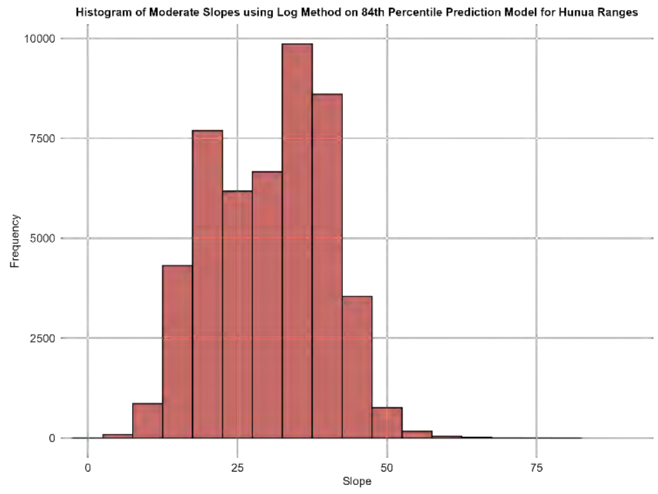
Low



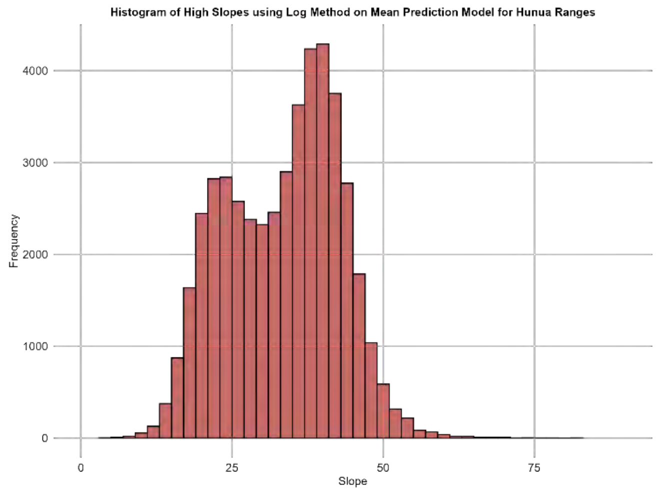


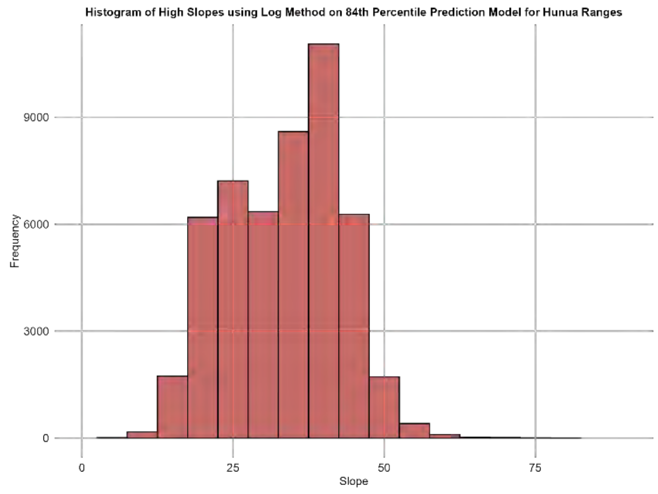
Moderate



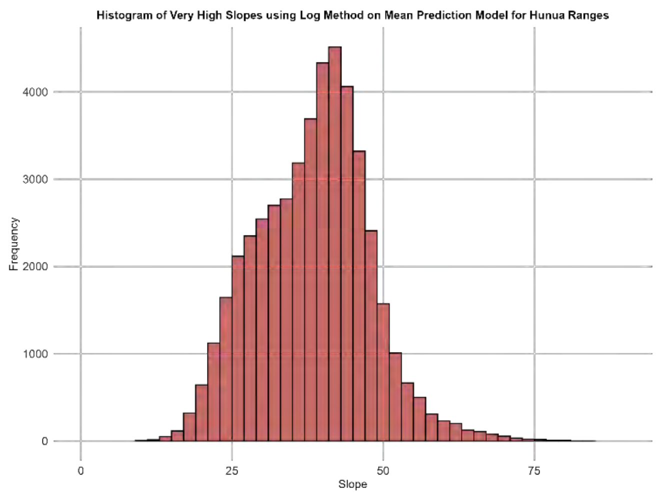


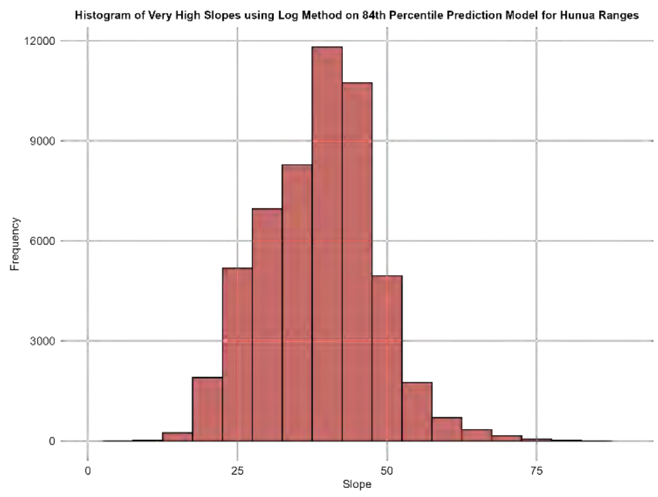
High





Very High

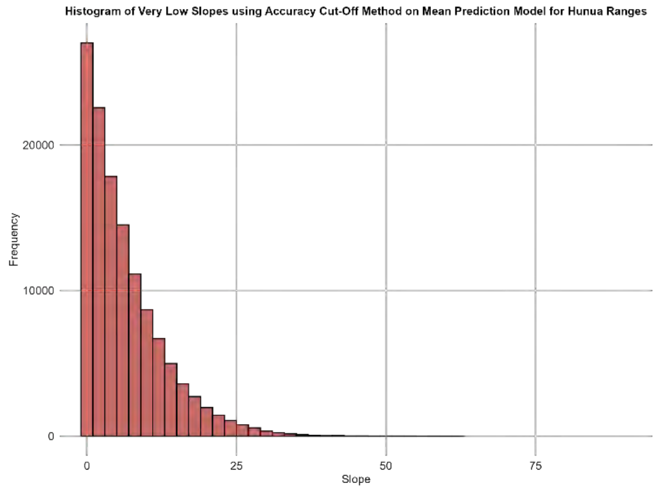


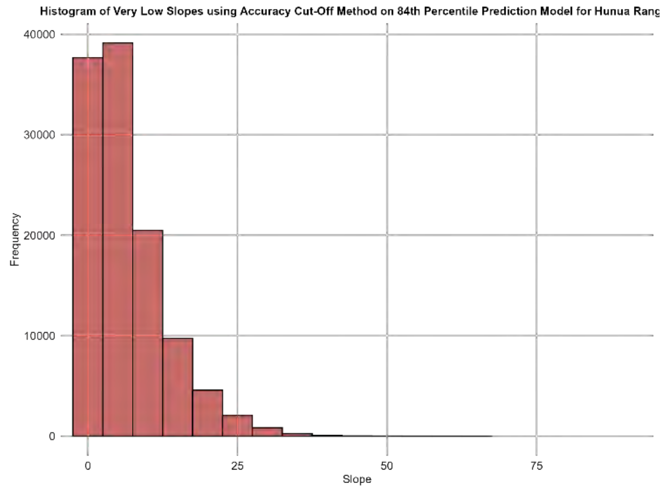


METHOD 3 (ACCURACY CUT-OFF)

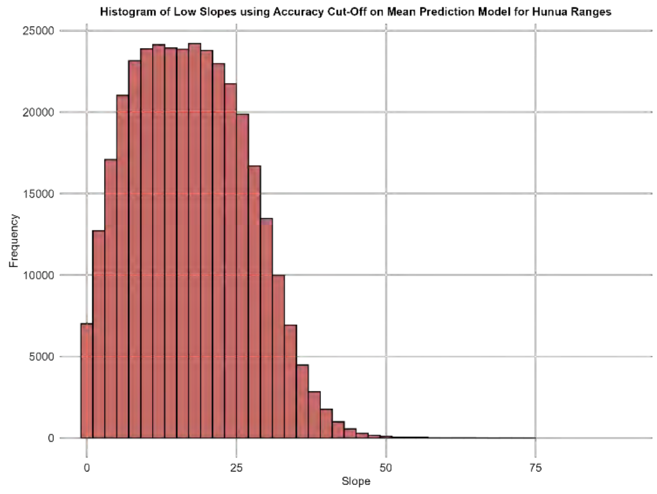
Mean predictions | 84th percentile predictions

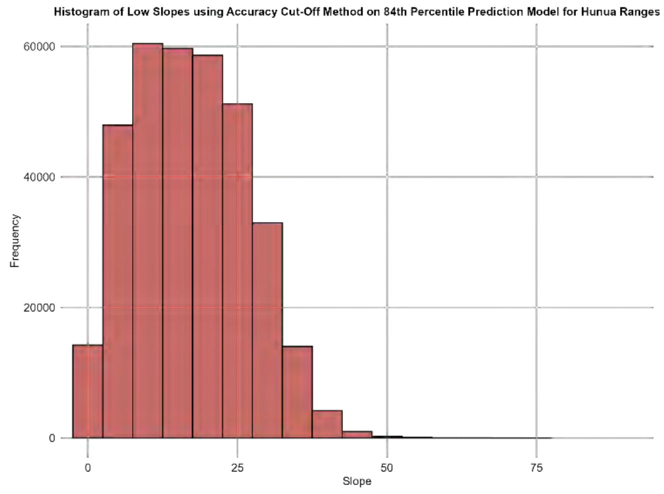
Very Low



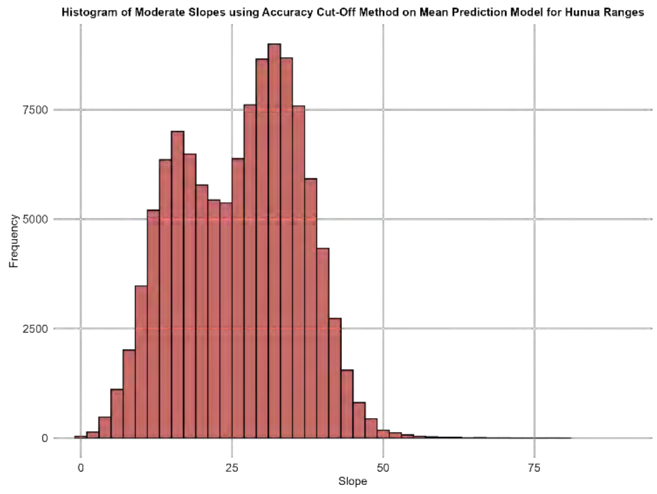


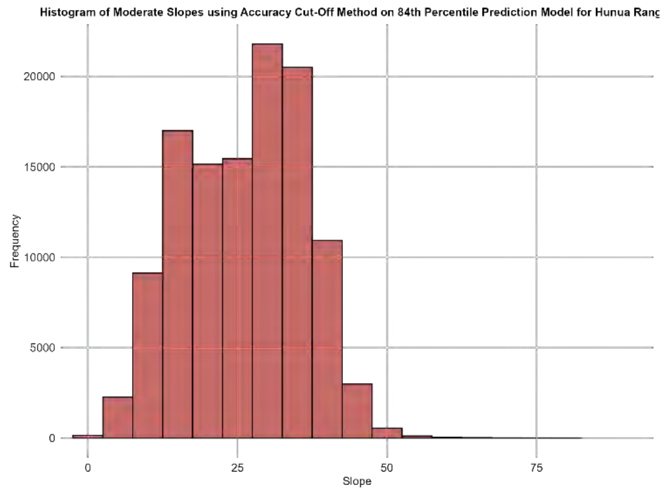
Low



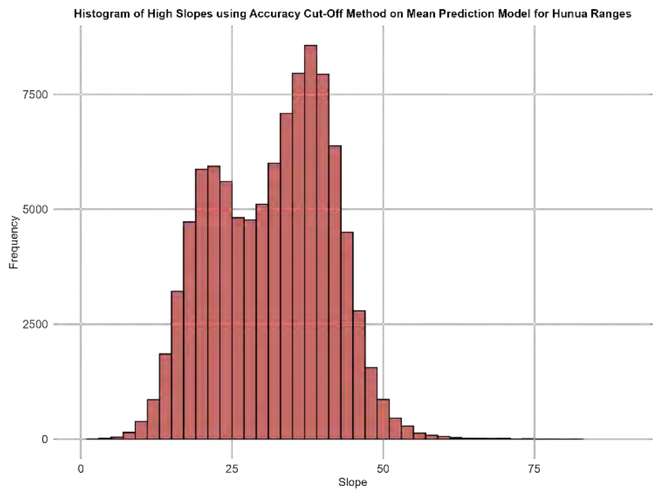


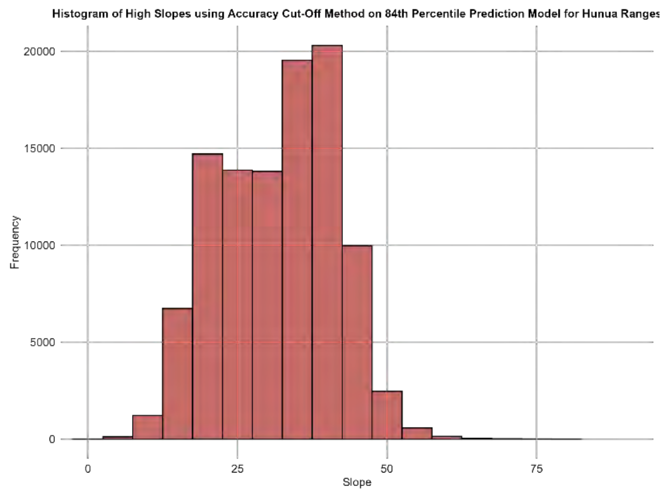
Moderate



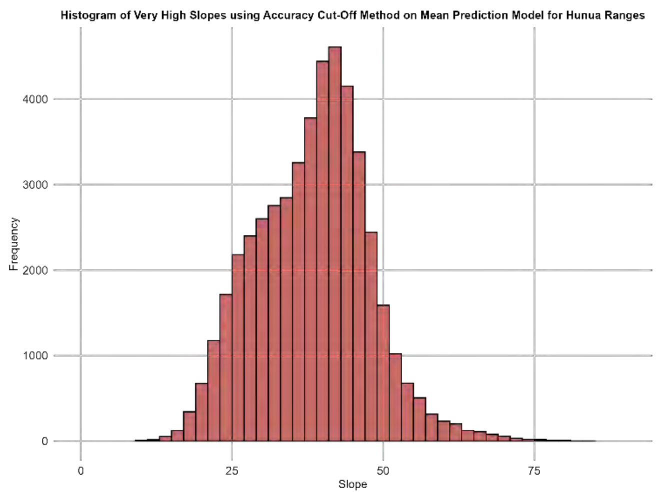


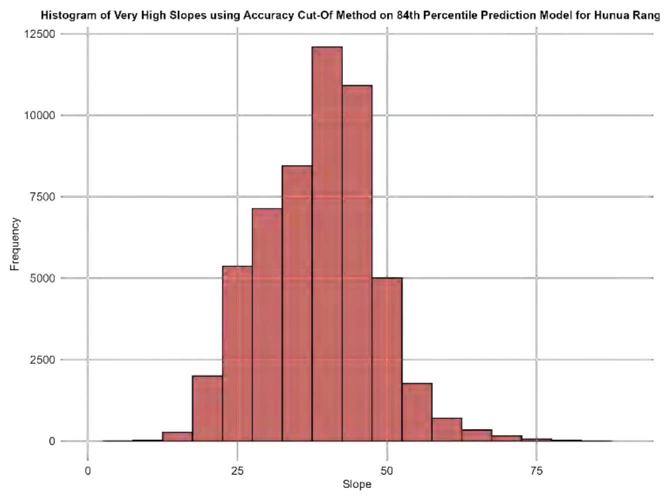
High





Very High



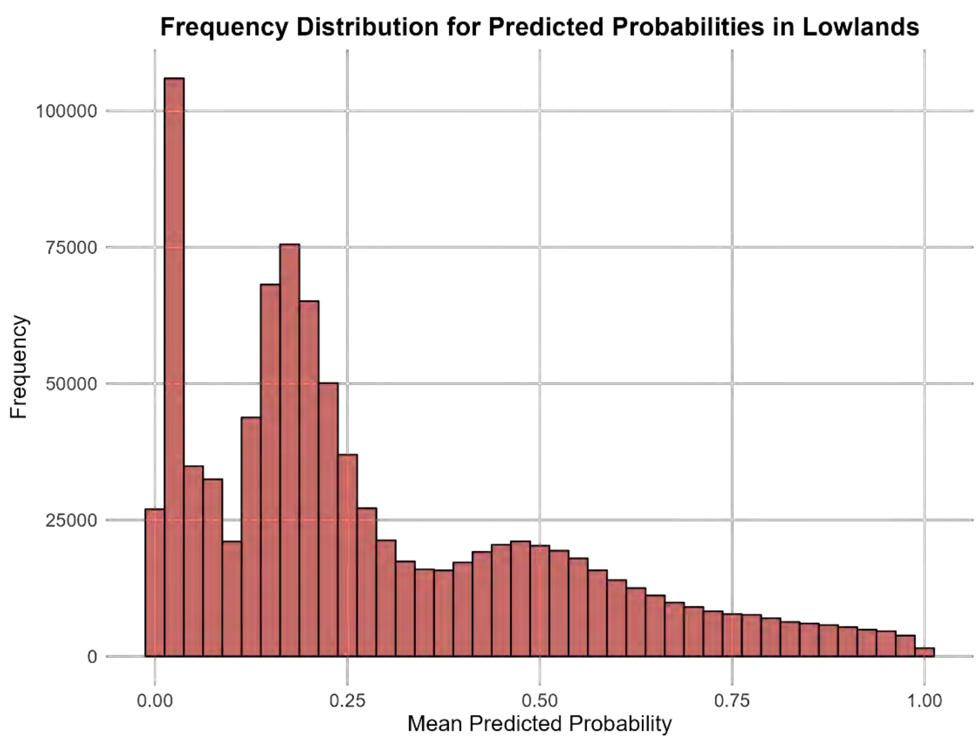


LOWLANDS WAITEMATA

MODEL COEFFICIENTS

Variable	Mean Coefficient	Standard Error	95% Confidence Interval	
			Upper Bound	Lower Bound
Intercept	-2.00479	0.011884	-1.9815	-2.02809
Aspect	-0.08103	0.000568	-0.07992	-0.08215
Curvature	0.030015	0.000202	0.030411	0.029619
GeolUnit2	0.769624	0.006233	0.781844	0.757404
GeolUnit3	-0.5824	0.013576	-0.55579	-0.60902
GeolUnit5	0.487185	0.044868	0.575146	0.399223
GeolUnit6	-0.61172	0.002956	-0.60593	-0.61752
GeolUnit7	-11.2706	0.067923	-11.1371	-11.404
GeolUnit8	1.437925	0.0015	1.440866	1.434984
GeolUnit9	5.088473	0.097389	5.279399	4.897547
GeolUnit10	1.584915	0.004798	1.594322	1.575508
GeolUnit11	2.108924	0.007491	2.12361	2.094239
GeolUnit12	0.962965	0.002022	0.966929	0.959001
GeolUnit13	0.097753	0.002563	0.102777	0.092729
Geomorphon2	2.699047	0.010987	2.720586	2.677507
Geomorphon3	2.728284	0.010141	2.748165	2.708402
Geomorphon4	0.801572	0.010716	0.822579	0.780565
Geomorphon5	2.601163	0.01013	2.621022	2.581304
Geomorphon6	2.47147	0.010077	2.491225	2.451715
Geomorphon7	2.807301	0.010169	2.827237	2.787365
Geomorphon8	1.685743	0.01026	1.705858	1.665629
Geomorphon9	2.664735	0.010171	2.684675	2.644795
Geomorphon10	3.390841	0.010749	3.411915	3.369768
DistanceToStream10	0.469804	0.007313	0.484141	0.455466
DistanceToStream20	0.099002	0.006201	0.11116	0.086845
DistanceToStream9999	-0.41426	0.005216	-0.40404	-0.42449
LCDB1	-1.01995	0.0041	-1.01191	-1.02799
LCDB2	-1.73222	0.003795	-1.72478	-1.73966
LCDB3	-1.88402	0.004816	-1.87458	-1.89346
LCDB4	-1.49639	0.003879	-1.48879	-1.504
LCDB5	-1.03679	0.005913	-1.02519	-1.04838
LCDB7	-0.06267	0.004159	-0.05452	-0.07082
LocalSlopeRelief	0.089592	0.000658	0.090881	0.088302
Slope	0.621272	0.000529	0.622309	0.620235
OLFP10	0.103576	0.002075	0.107645	0.099508
OLFP9999	0.149922	0.001582	0.153023	0.14682

PROBABILITY DISTRIBUTION



AREA COMPARISONS

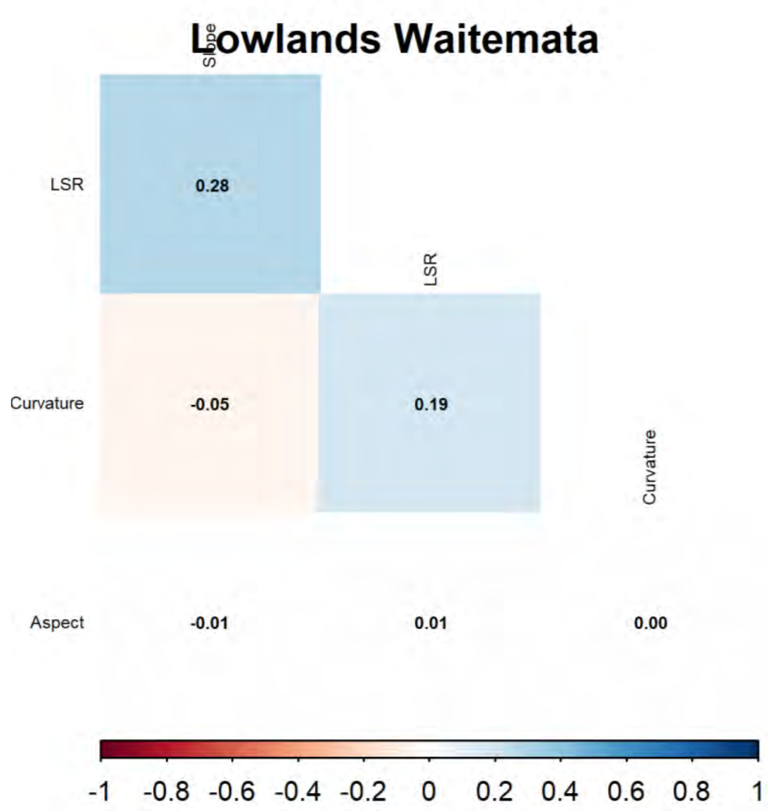
	Land area comparison					
	Lowlands Waitemata					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	90.9%	90.0%	75.0%	72.8%	89.6%	88.6%
Low	6.5%	7.1%	6.2%	7.7%	4.2%	4.5%
Moderate	2.0%	2.2%	6.3%	5.9%	2.6%	3.0%
High	0.6%	0.7%	6.2%	6.6%	2.1%	2.2%
Very High			6.2%	7.0%	1.6%	1.8%

	Landslide inventory density (landslide area per class/total landslide area per region)					
	Lowlands Waitemata					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	25.0%	20.7%	7.6%	5.7%	22.3%	18.4%
Low	25.0%	23.9%	4.1%	4.1%	10.5%	9.3%
Moderate	25.0%	26.4%	7.5%	6.1%	10.4%	11.0%
High	25.0%	29.0%	13.6%	11.9%	17.8%	17.0%
Very High			67.2%	72.3%	39.0%	44.2%

	Landslide number density (landslide cells/total cells per region)					
	Lowlands Waitemata					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Low	0.4%	0.3%	0.1%	0.0%	0.2%	0.2%
Moderate	1.2%	1.1%	0.1%	0.1%	0.4%	0.3%
High	4.0%	4.0%	0.2%	0.2%	0.8%	0.7%
Very High			1.0%	1.0%	2.4%	2.4%

VARIABLE CORRELATIONS

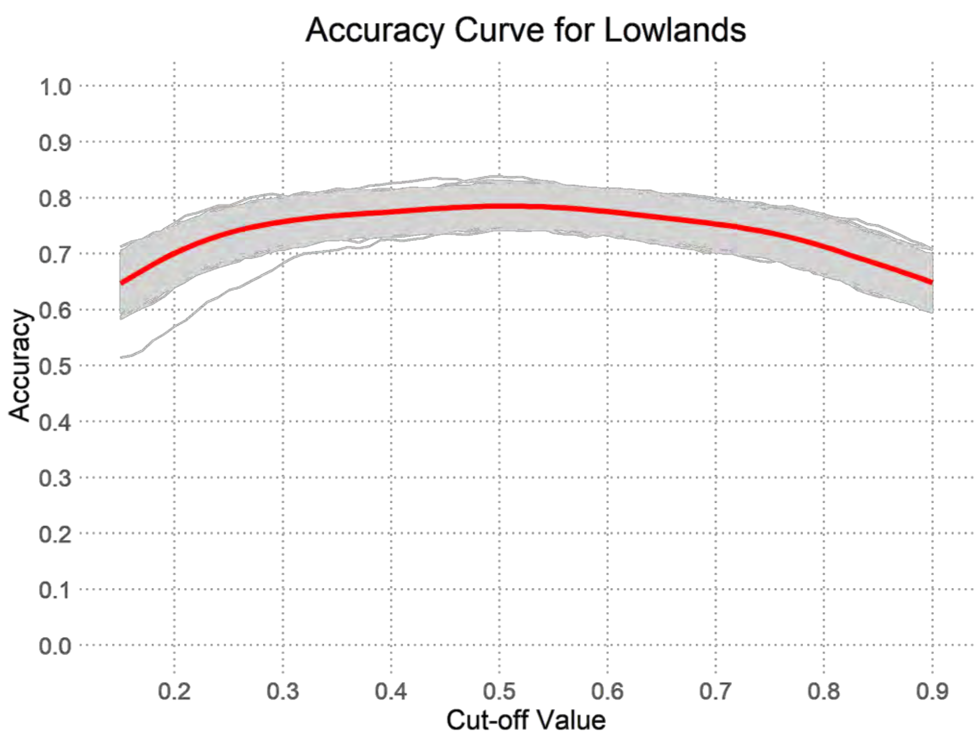
Continuous Variables



Categorical Variables

GeolUnit_vs_Geomorphon	0.111883624
GeolUnit_vs_DistanceToStream	0.058267653
GeolUnit_vs_LCDB	0.179536305
GeolUnit_vs_OLFP	0.058055888
Geomorphon_vs_DistanceToStream	0.193844604
Geomorphon_vs_LCDB	0.137551244
Geomorphon_vs_OLFP	0.218466355
DistanceToStream_vs_LCDB	0.090294668
DistanceToStream_vs_OLFP	0.099367635
LCDB_vs_OLFP	0.028065084

ACCURACY PLOT

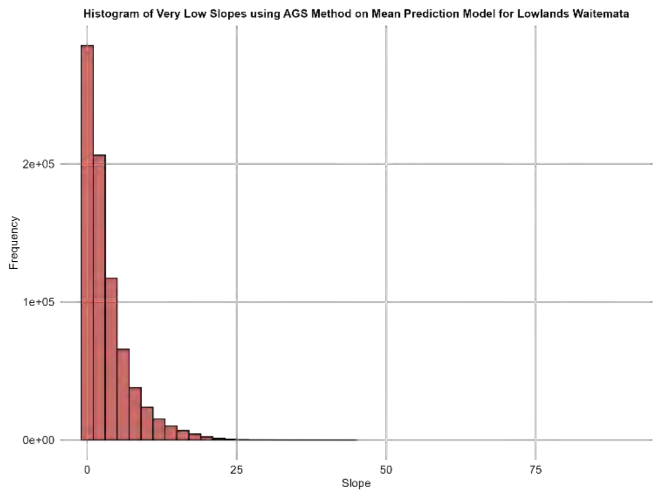


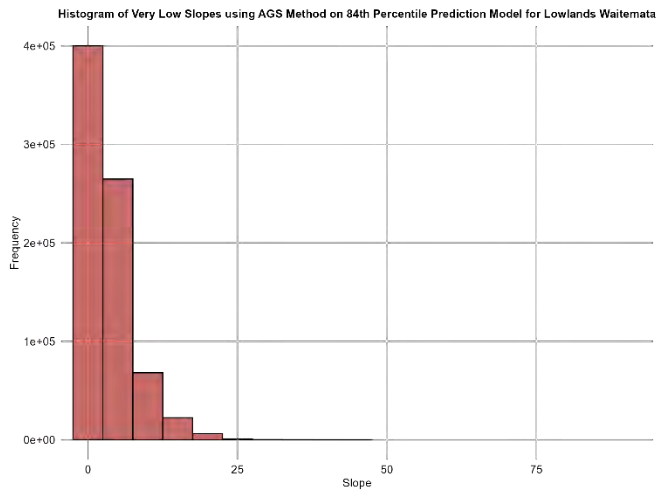
SLOPE ANGLE DISTRIBUTIONS

METHOD 1 (AGS)

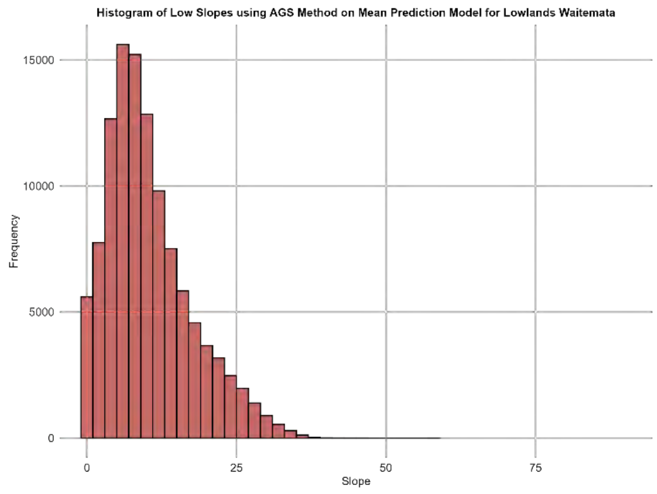
Mean predictions | 84^{th} percentile predictions

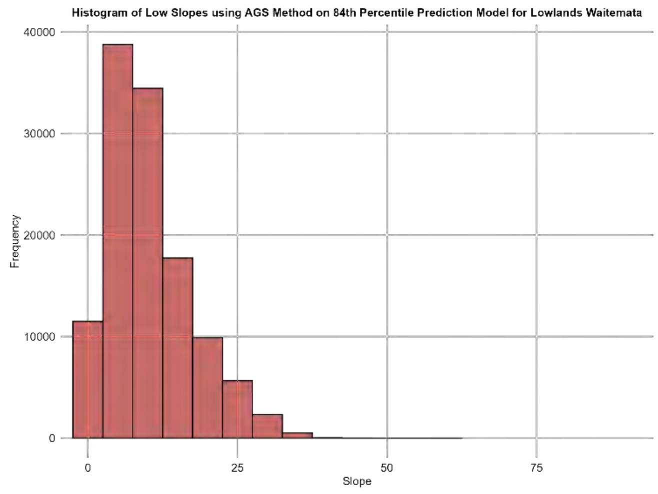
Very Low



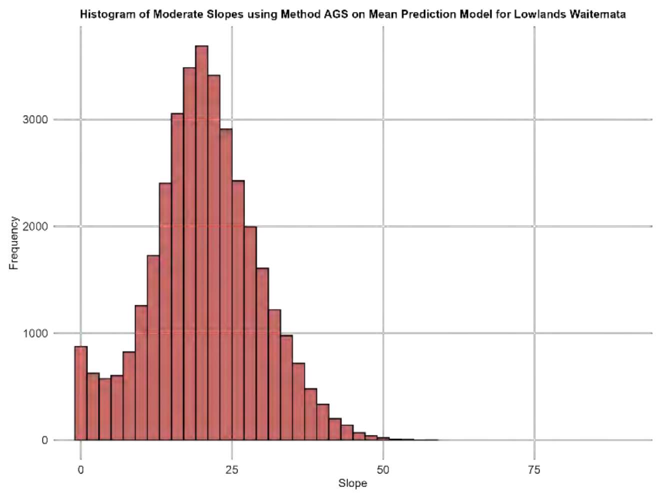


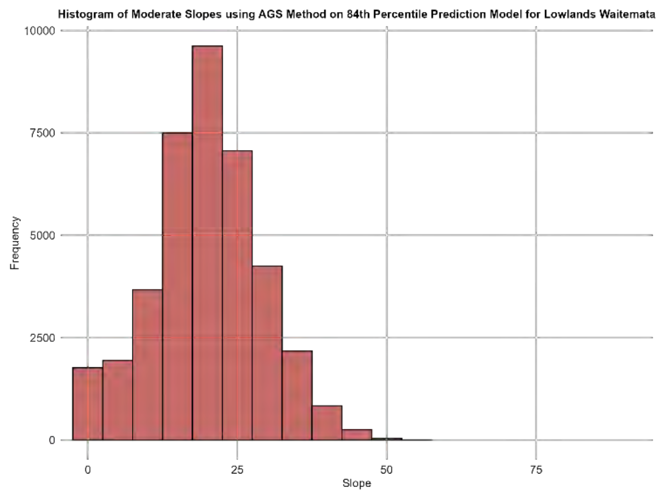
Low



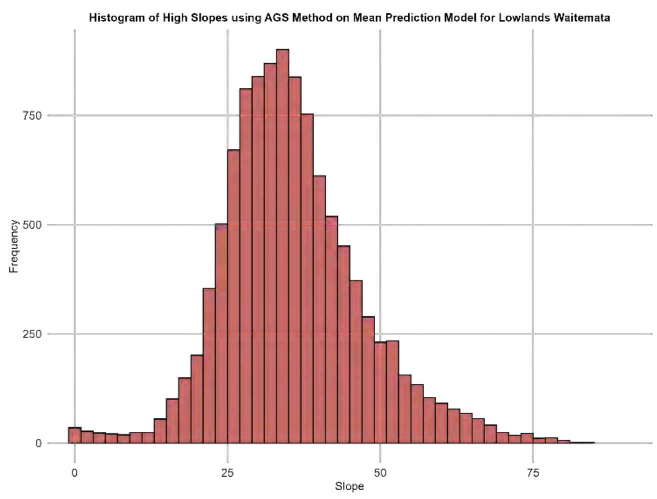


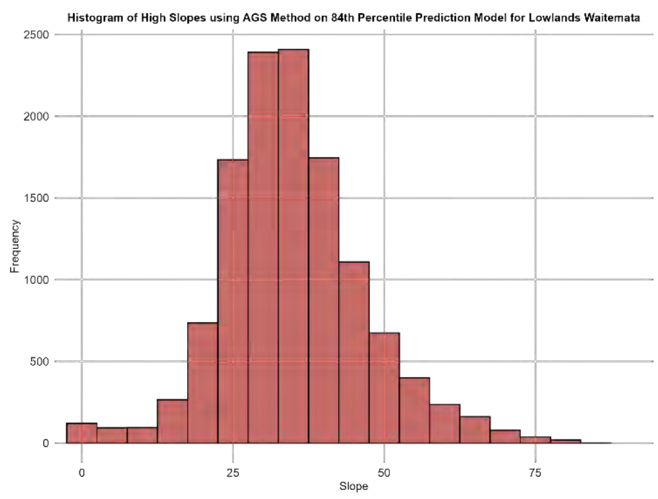
Moderate





High



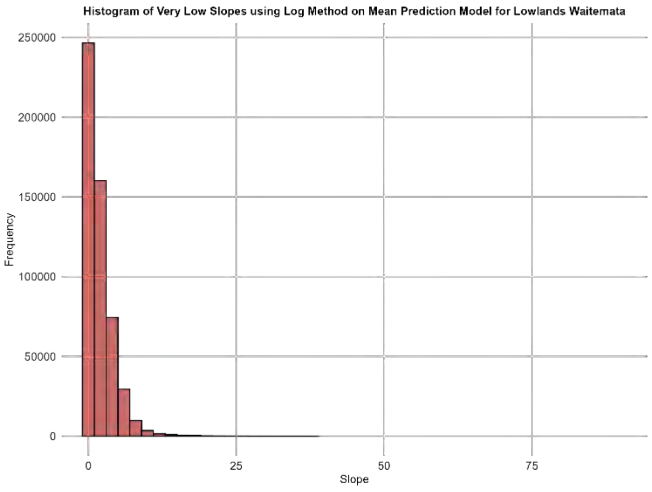


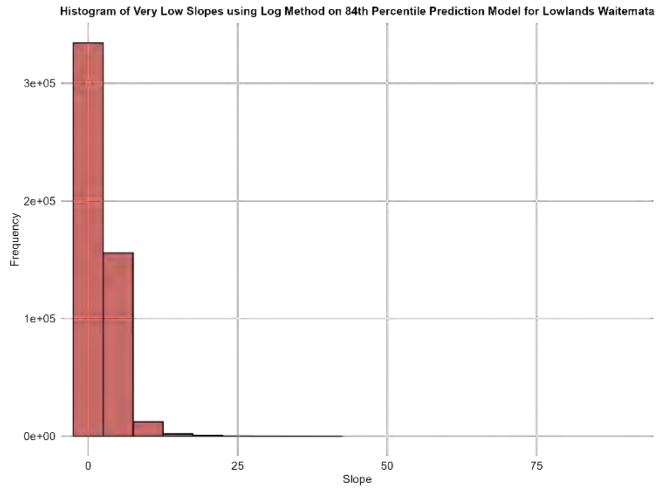
METHOD 2 (LOG BINS)

Mean predictions

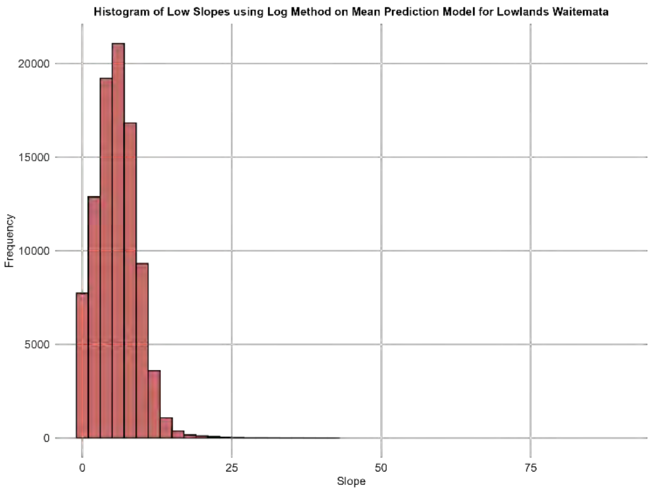
84th percentile predictions

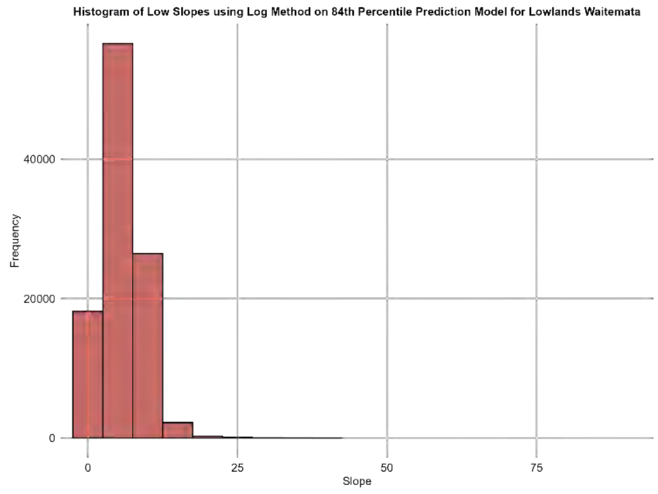
Very Low



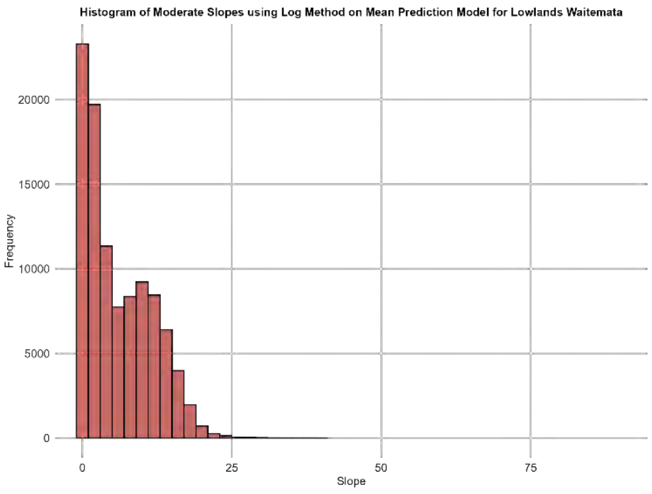


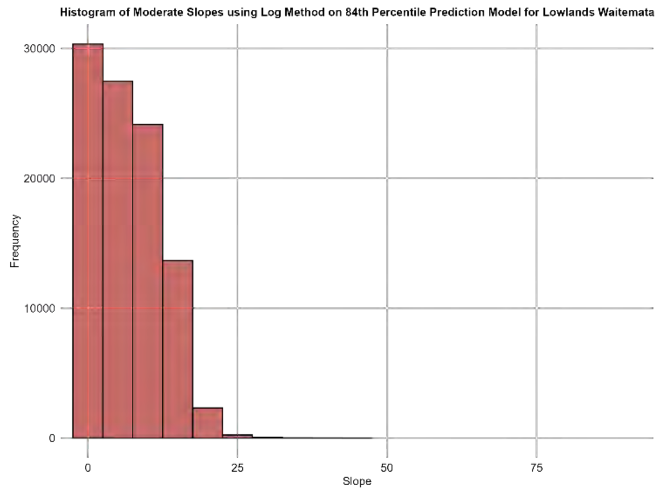
Low



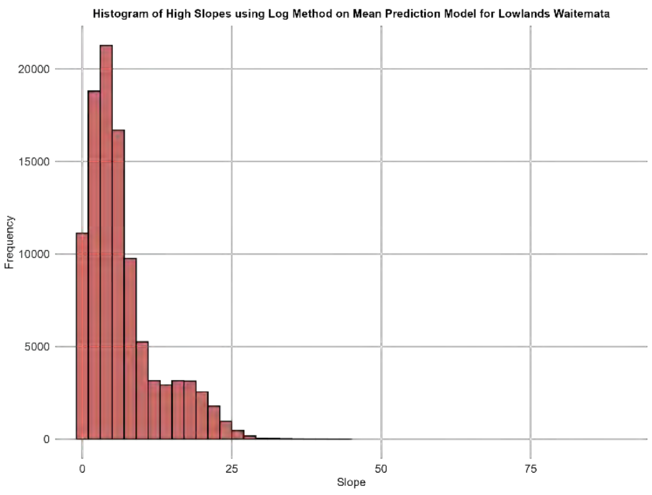


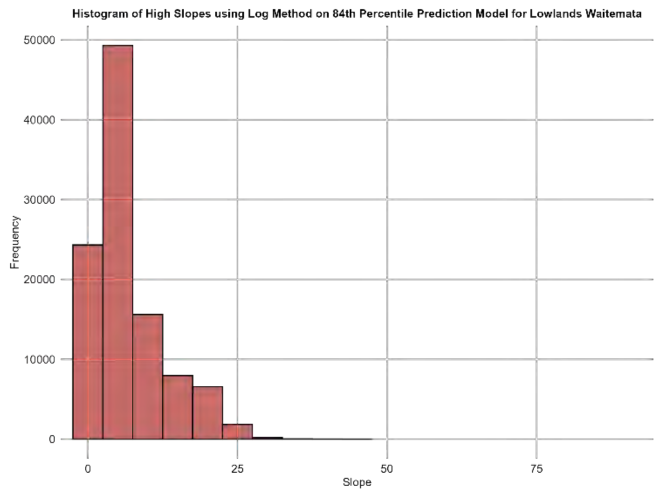
Moderate



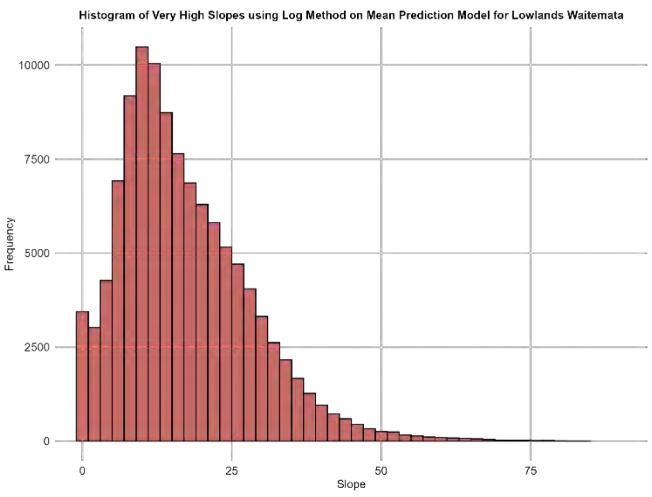


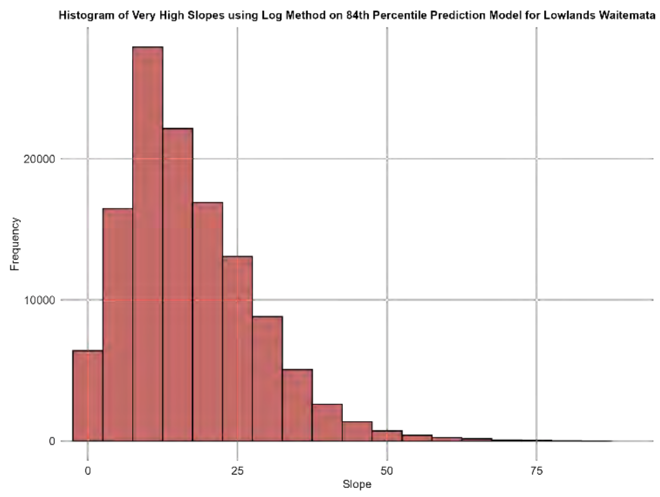
High





Very High

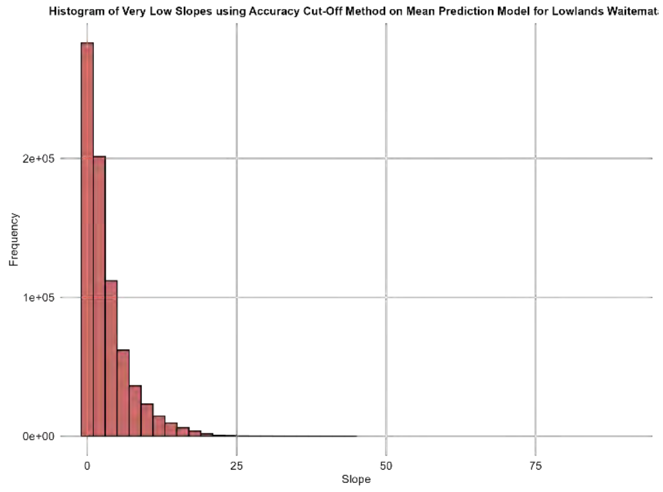


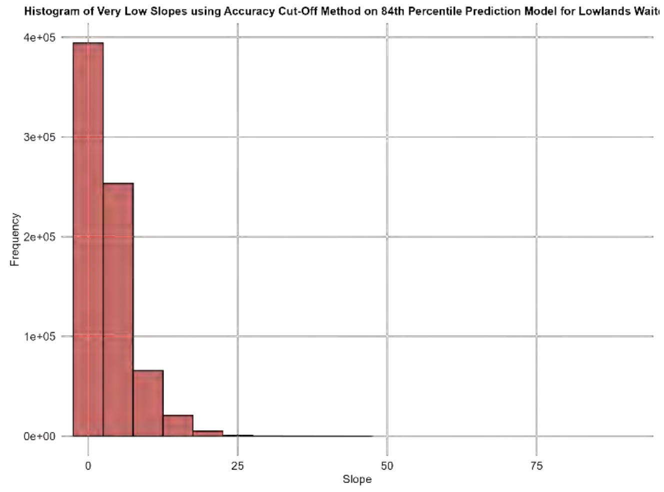


METHOD 3 (ACCURACY CUT-OFF)

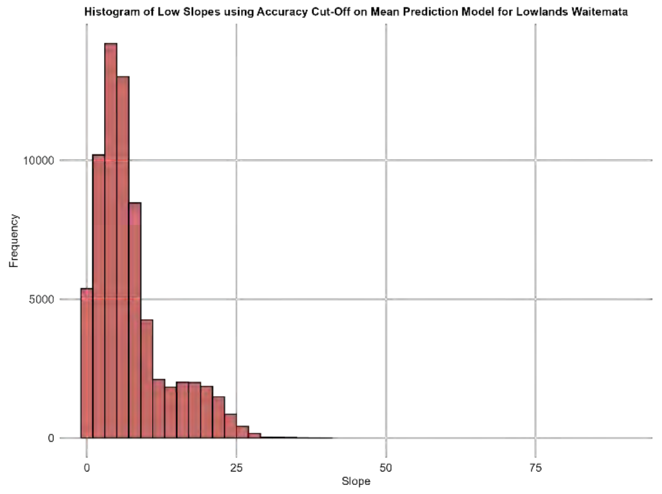
Mean predictions | 84th percentile predictions

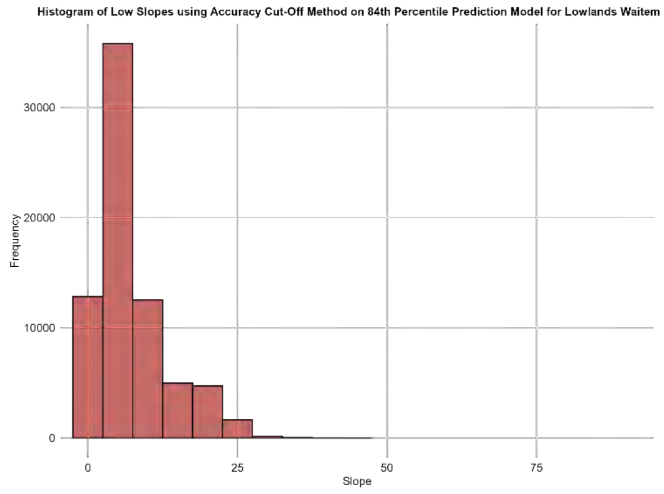
Very Low



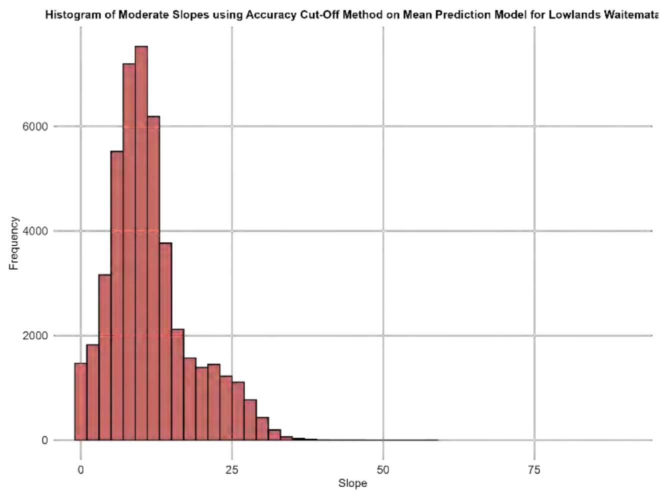


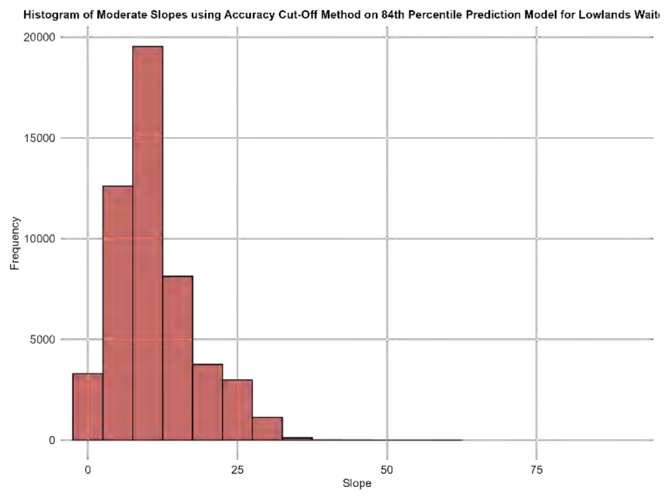
Low



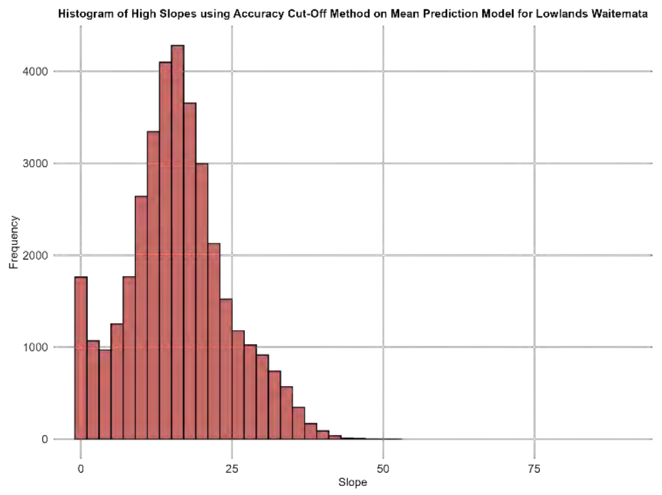


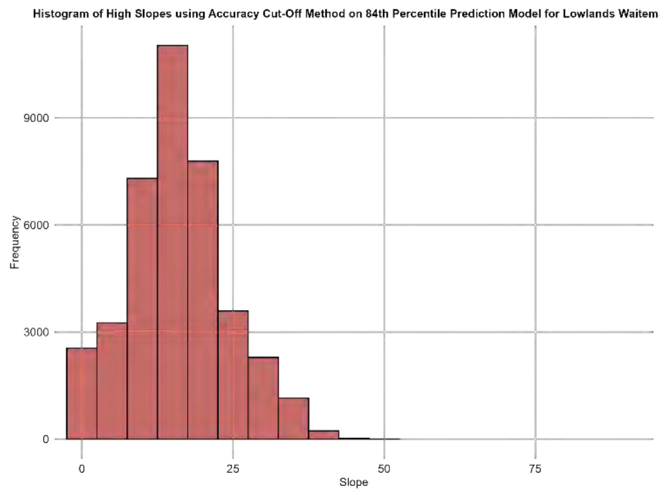
Moderate



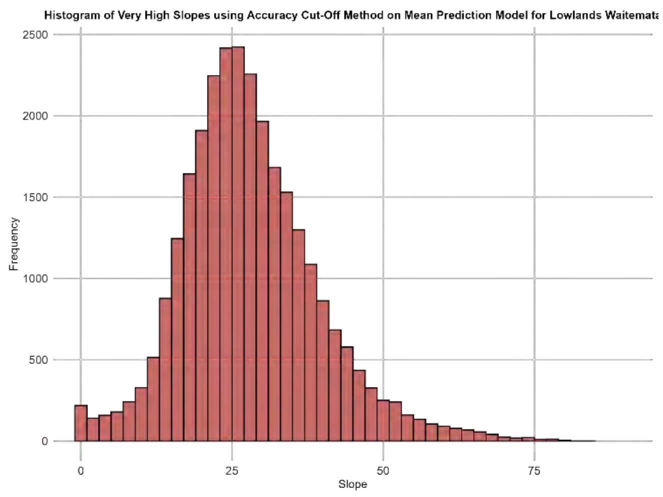


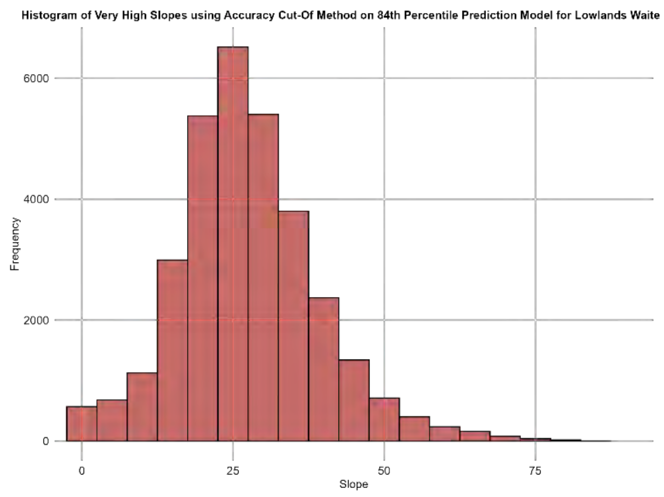
High





Very High



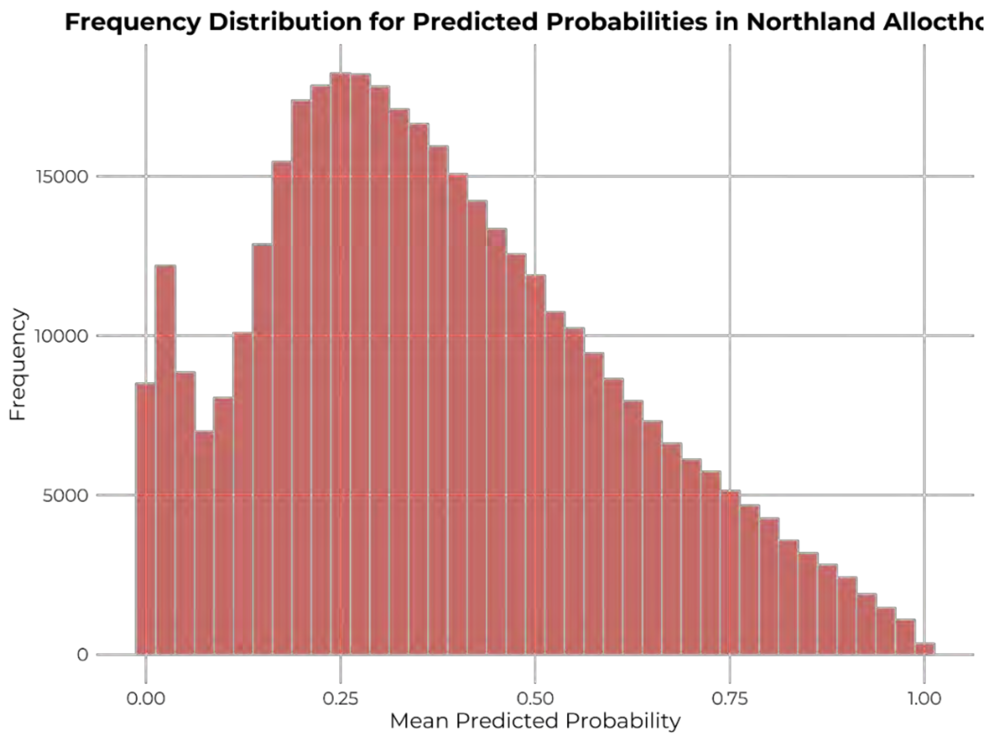


NORTHLAND ALLOCHTHON

MODEL COEFFICIENTS

Variable	Mean Coefficient	Standard Error	95% Confidence Interval	
			Upper Bound	Lower Bound
Intercept	-1.5E+12	1.06E+12	5.64E+11	-3.6E+12
Curvature	-5.2E+10	4.43E+10	3.49E+10	-1.4E+11
Geomorphon2	5.21E+11	3.74E+11	1.25E+12	-2.1E+11
Geomorphon3	6.56E+11	4.66E+11	1.57E+12	-2.6E+11
Geomorphon4	-2.6E+11	1.84E+11	1.01E+11	-6.2E+11
Geomorphon5	6.08E+11	4.37E+11	1.47E+12	-2.5E+11
Geomorphon6	7.16E+11	5.08E+11	1.71E+12	-2.8E+11
Geomorphon7	7.74E+11	5.53E+11	1.86E+12	-3.1E+11
Geomorphon8	4.35E+11	3.08E+11	1.04E+12	-1.7E+11
Geomorphon9	8.93E+11	6.35E+11	2.14E+12	-3.5E+11
Geomorphon10	1.23E+12	8.75E+11	2.94E+12	-4.9E+11
LCDB1	6.24E+11	5.29E+11	1.66E+12	-4.1E+11
LCDB2	2.06E+11	1.36E+11	4.72E+11	-6E+10
LCDB3	3.28E+11	3.17E+11	9.5E+11	-2.9E+11
LCDB4	8.09E+11	5.61E+11	1.91E+12	-2.9E+11
LCDB5	-3.9E+11	4.07E+11	4.07E+11	-1.2E+12
LCDB7	1.56E+10	1.56E+10	4.62E+10	-1.5E+10
LocalSlopeRelief	2.24E+11	1.61E+11	5.39E+11	-9.1E+10
Slope	2.85E+11	2.04E+11	6.85E+11	-1.2E+11
OLFP10	-3.5E+10	4.3E+10	4.95E+10	-1.2E+11
OLFP9999	-1E+11	7.27E+10	4.27E+10	-2.4E+11
Aspect	5.94E+09	1.7E+10	3.93E+10	-2.7E+10
DistanceToStream10	1.26E+11	1.46E+11	4.12E+11	-1.6E+11
DistanceToStream20	1.59E+11	2.06E+11	5.63E+11	-2.4E+11
DistanceToStream9999	-7.4E+10	5.98E+10	4.3E+10	-1.9E+11
GeolUnit7	-5.2E+11	5.17E+11	4.97E+11	-1.5E+12
GeolUnit8	-3.4E+11	3.41E+11	3.28E+11	-1E+12
GeolUnit10	3.85E+12	3.85E+12	1.14E+13	-3.7E+12

PROBABILITY DISTRIBUTION



AREA COMPARISONS

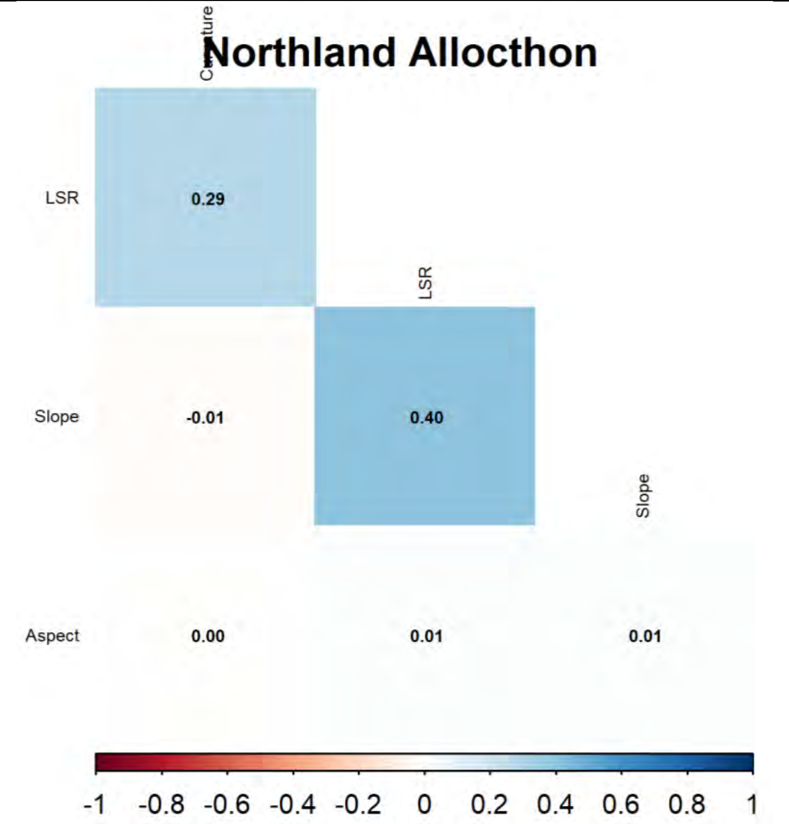
	Land area comparison					
	Northland Allochthon					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	13.0%	11.4%	75.0%	71.9%	39.1%	35.0%
Low	56.8%	55.1%	6.3%	6.7%	34.3%	35.0%
Moderate	17.8%	19.1%	6.2%	6.9%	11.4%	12.4%
High	12.4%	14.4%	6.2%	7.0%	8.8%	9.8%
Very High			6.3%	7.5%	6.5%	7.8%

	Landslide inventory density (landslide area per class/total landslide area per region)					
	Northland Allochthon					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	1.0%	0.8%	30.3%	25.5%	7.5%	5.3%
Low	24.0%	19.8%	8.4%	8.1%	21.2%	18.5%
Moderate	25.0%	24.0%	10.9%	10.7%	15.4%	15.4%
High	50.0%	55.4%	16.9%	17.4%	21.9%	21.7%
Very High			33.4%	38.3%	33.9%	39.1%

	Landslide number density (landslide cells/total cells per region)					
	Northland Allochthon					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	0.0%	0.0%	0.2%	0.2%	0.1%	0.1%
Low	0.2%	0.2%	0.6%	0.5%	0.3%	0.2%
Moderate	0.6%	0.5%	0.7%	0.7%	0.6%	0.5%
High	1.7%	1.6%	1.1%	1.1%	1.1%	0.9%
Very High			2.3%	2.2%	2.2%	2.1%

VARIABLE CORRELATIONS

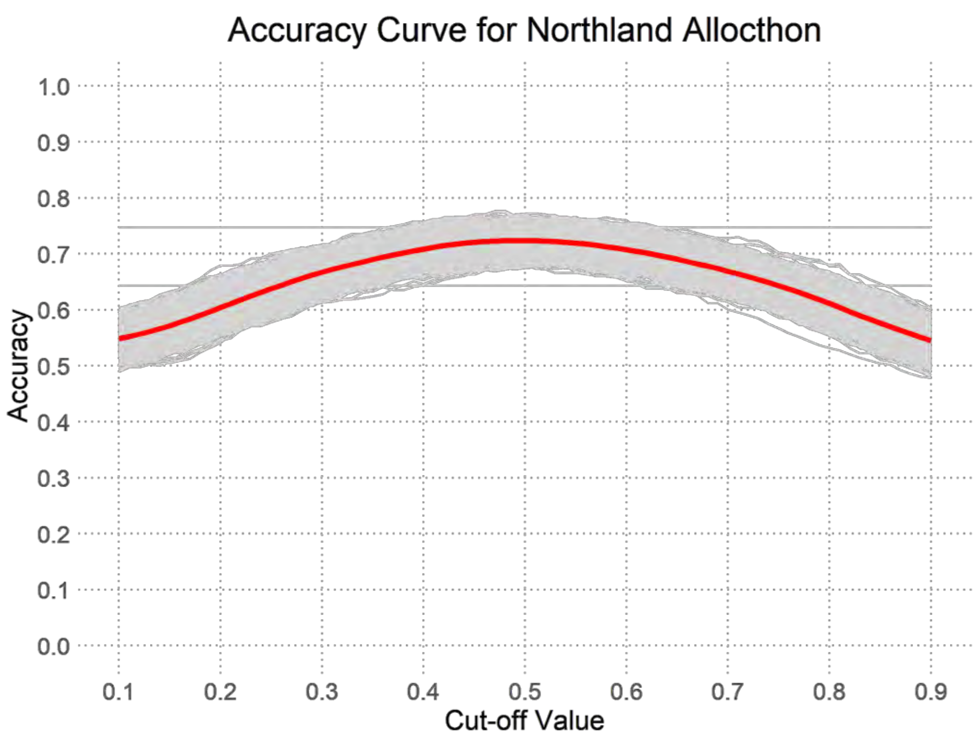
Continuous Variables



Categorical Variables

GeolUnit_vs_Geomorphon	0.213252054
GeolUnit_vs_DistanceToStream	0.070301506
GeolUnit_vs_LCDB	0.152993348
GeolUnit_vs_OLFP	0.063264593
Geomorphon_vs_DistanceToStream	0.225091608
Geomorphon_vs_LCDB	0.125420634
Geomorphon_vs_OLFP	0.246913135
DistanceToStream_vs_LCDB	0.054671948
DistanceToStream_vs_OLFP	0.113487675
LCDB_vs_OLFP	0.036751542

ACCURACY PLOT



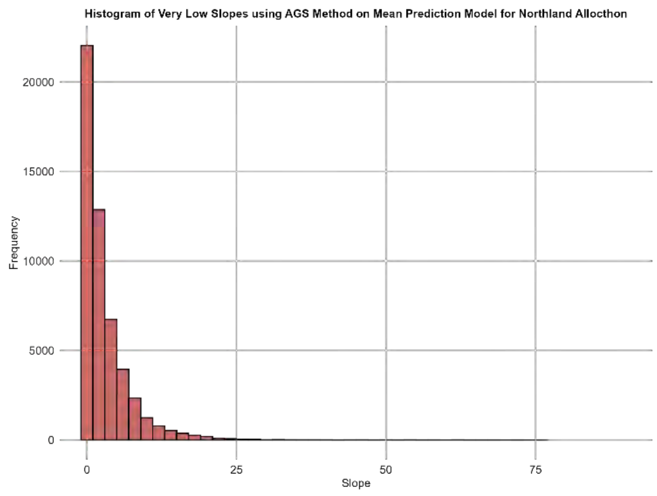
SLOPE ANGLE DISTRIBUTIONS

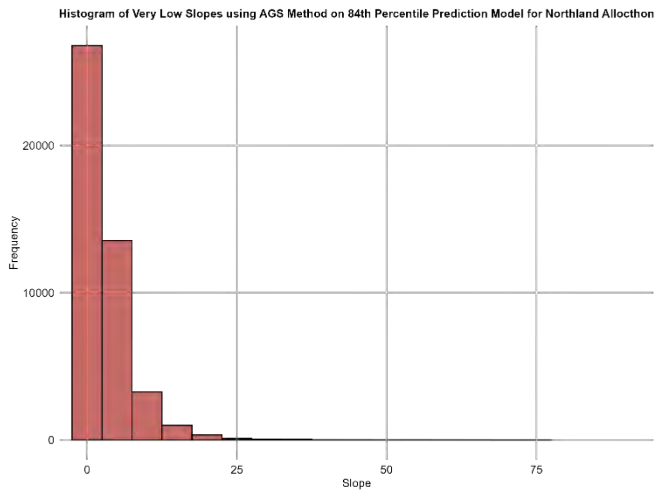
METHOD 1 (AGS)

Mean predictions

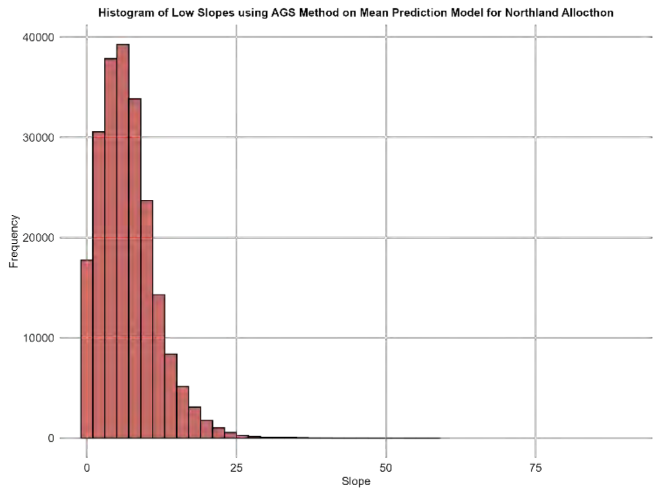
84th percentile predictions

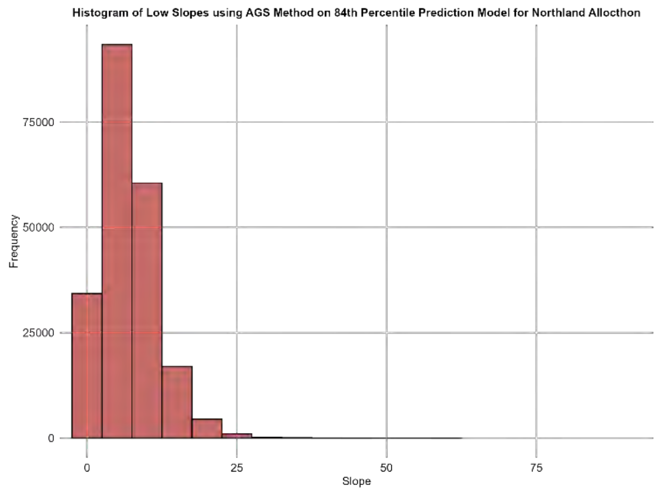
Very Low



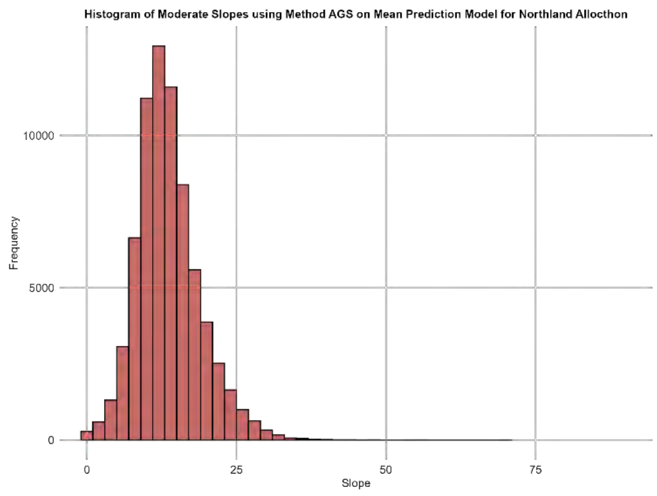


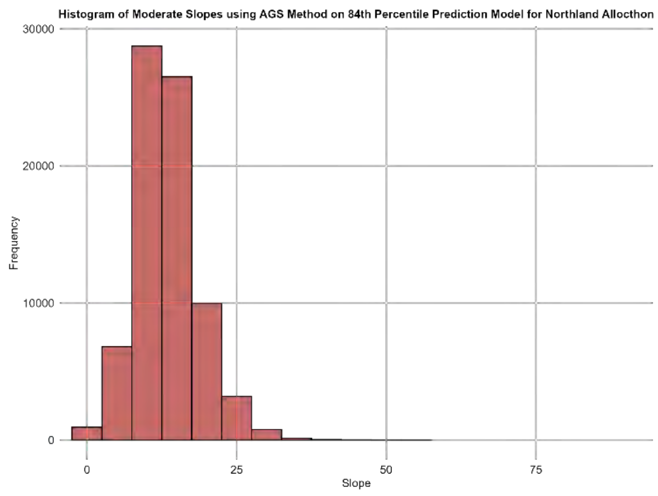
Low



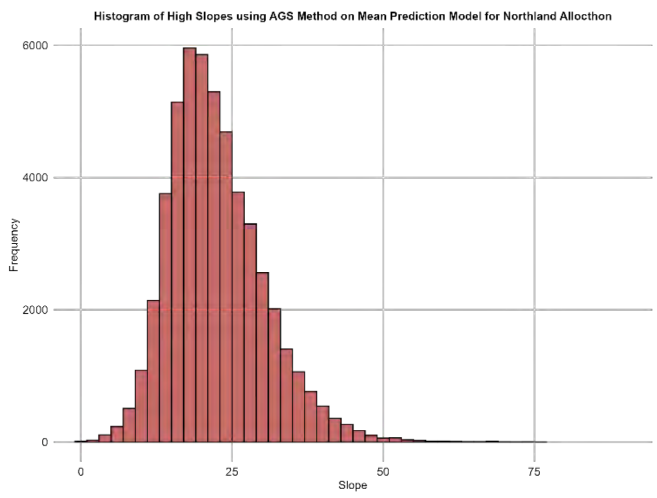


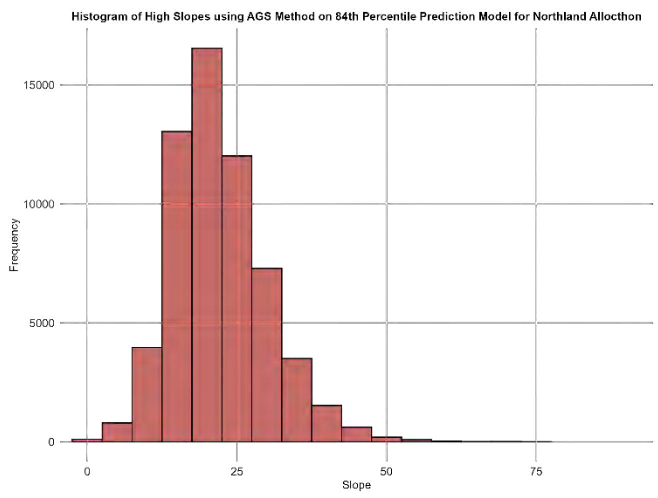
Moderate





High

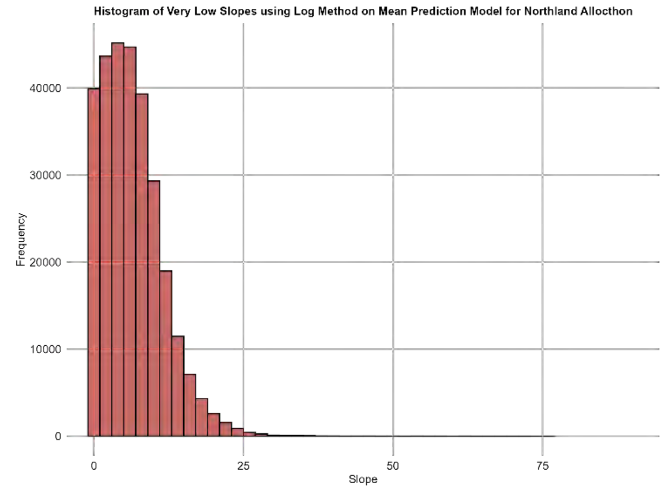


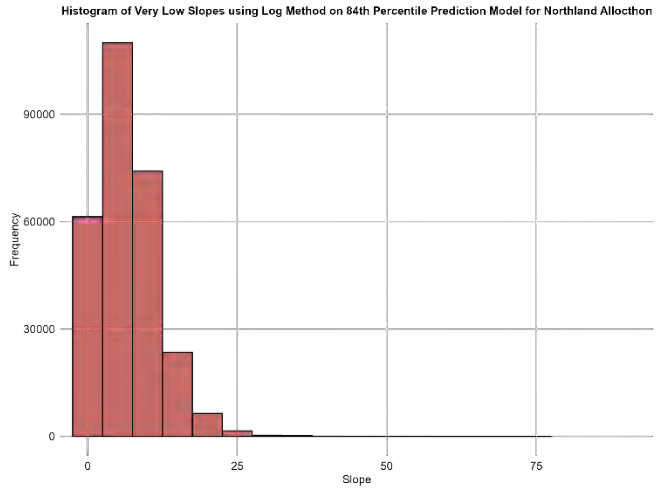


METHOD 2 (LOG BINS)

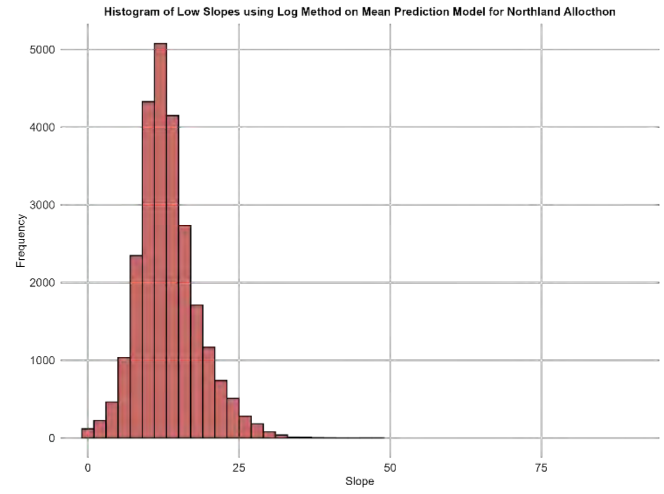
Mean predictions | 84th percentile predictions

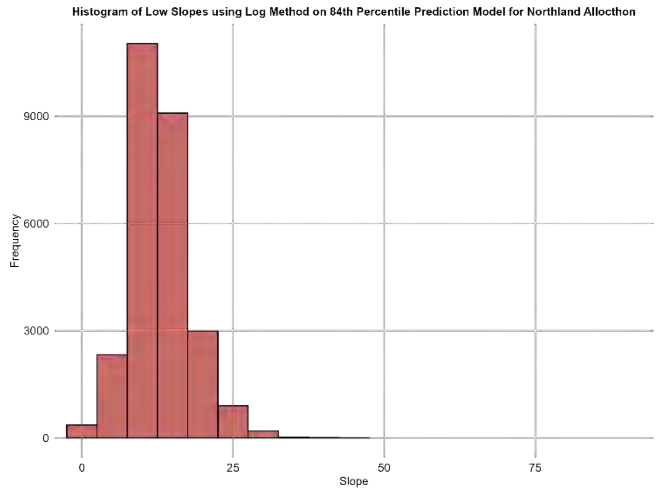
Very Low



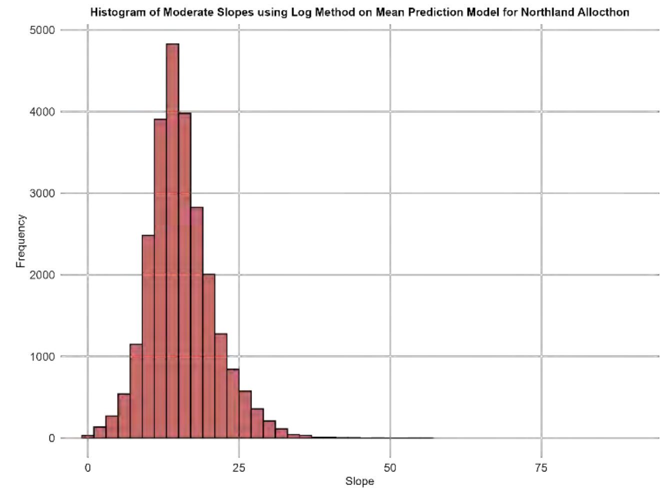


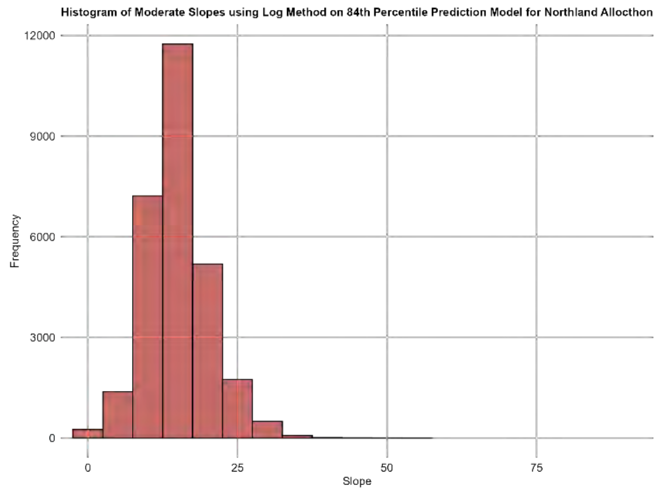
Low



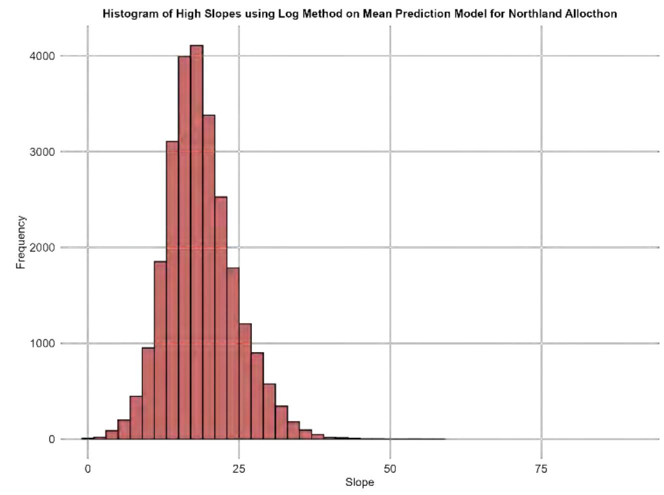


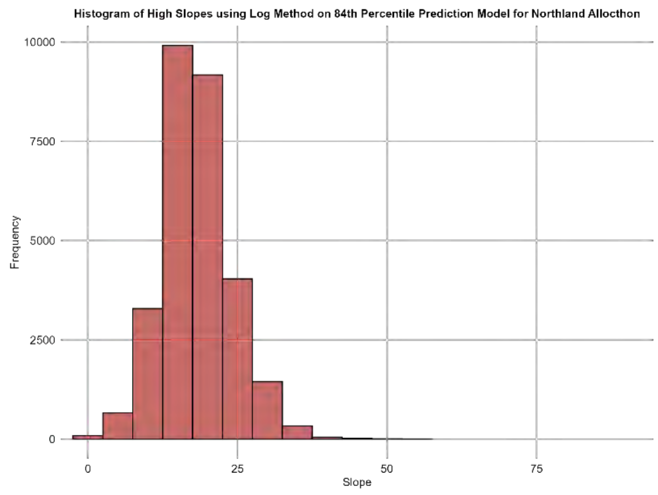
Moderate



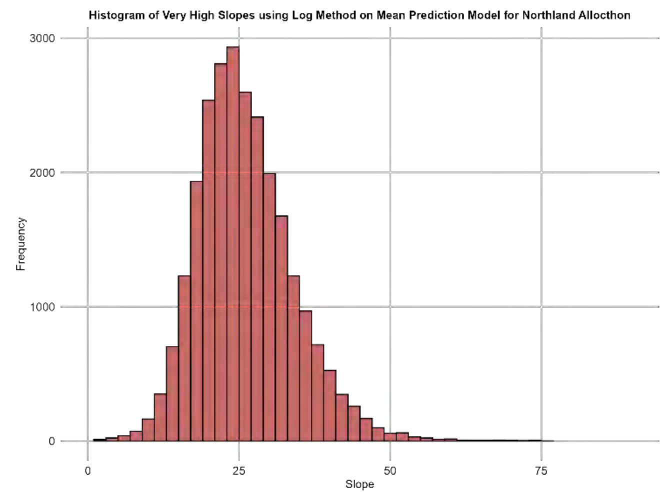


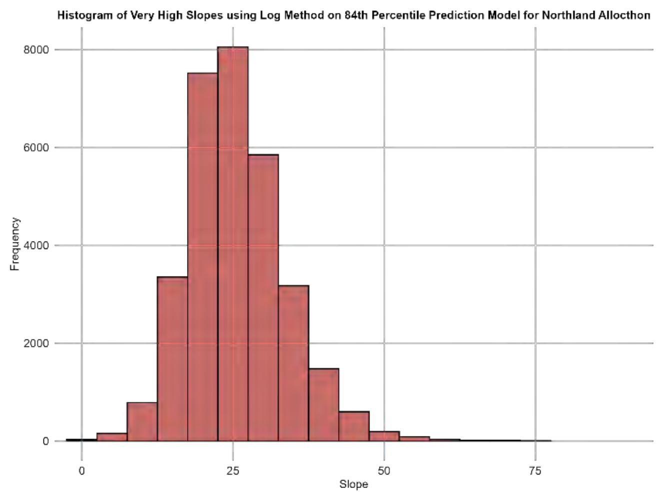
High





Very High

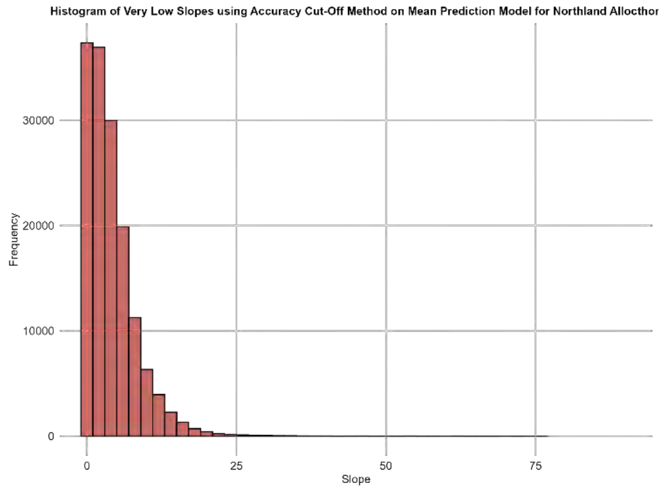


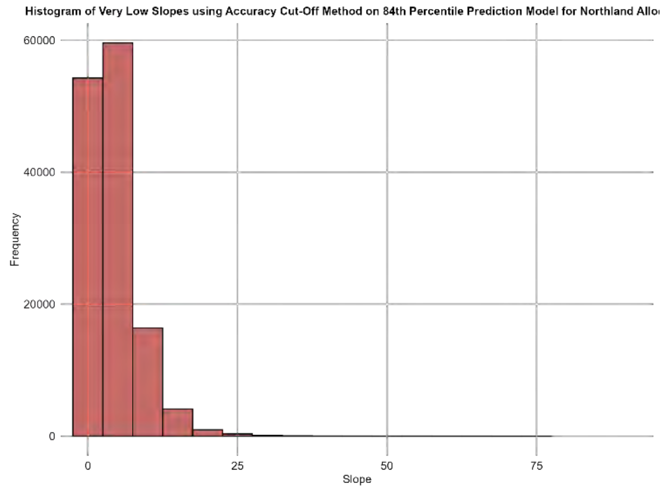


METHOD 3 (ACCURACY CUT-OFF)

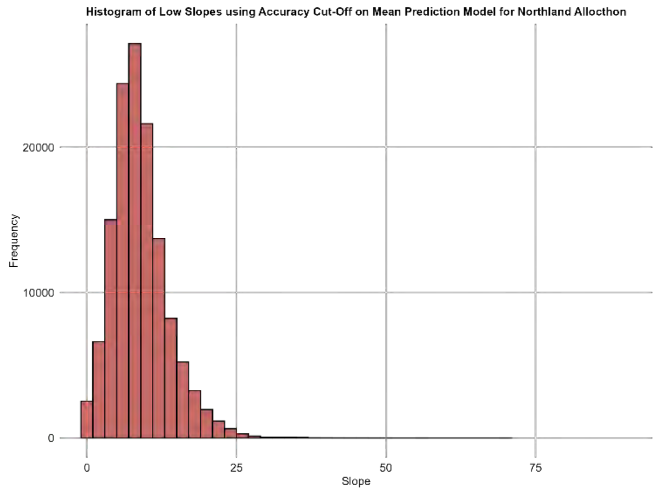
Mean predictions | 84th percentile predictions

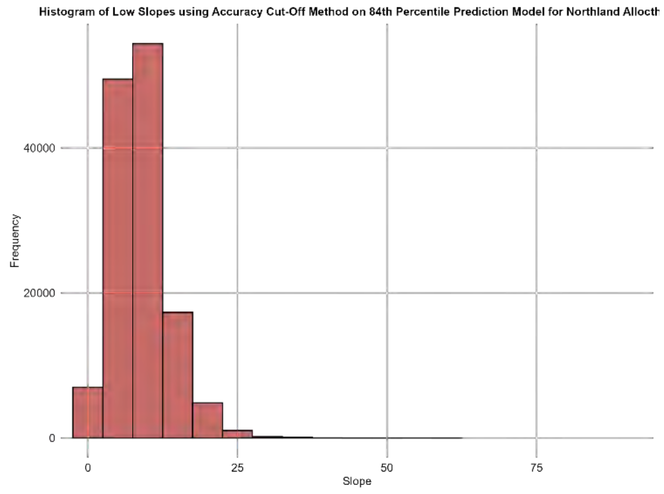
Very Low



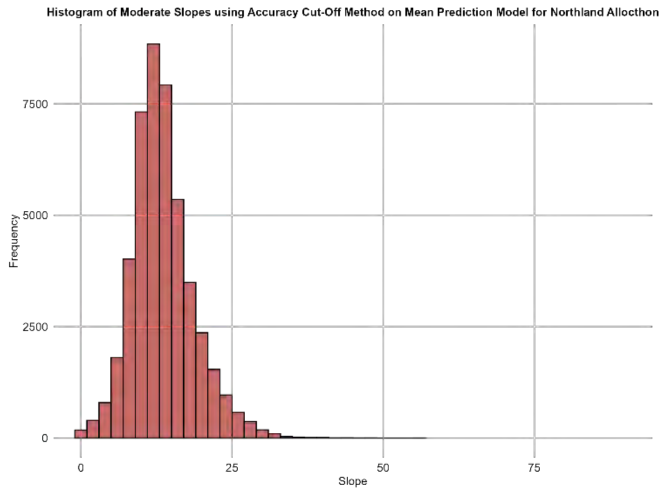


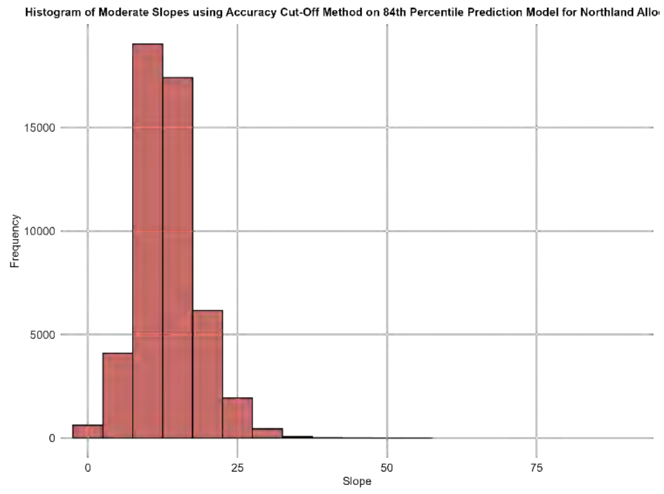
Low



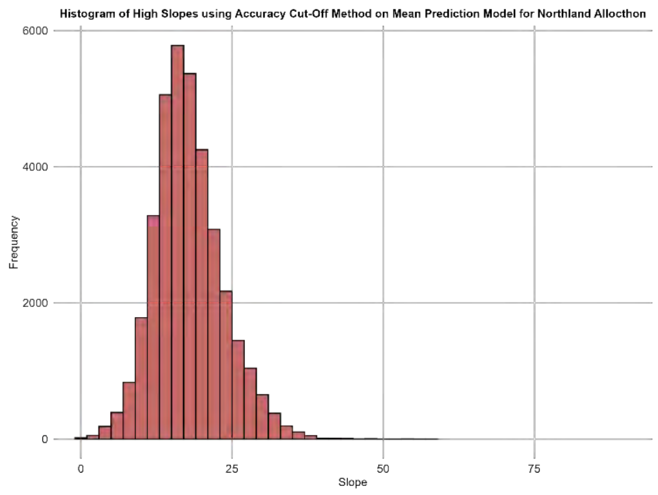


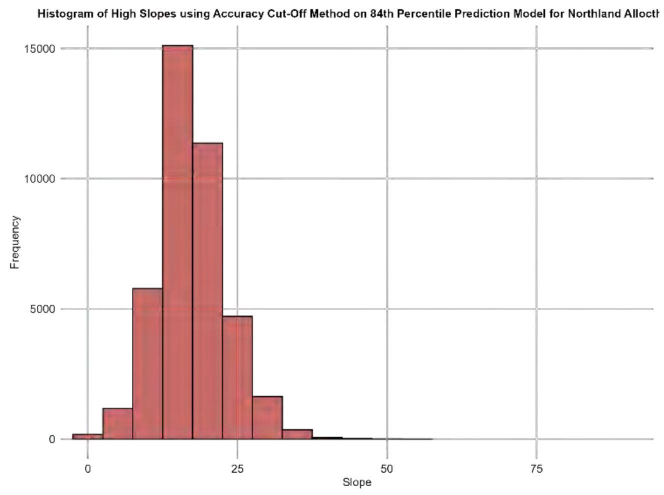
Moderate



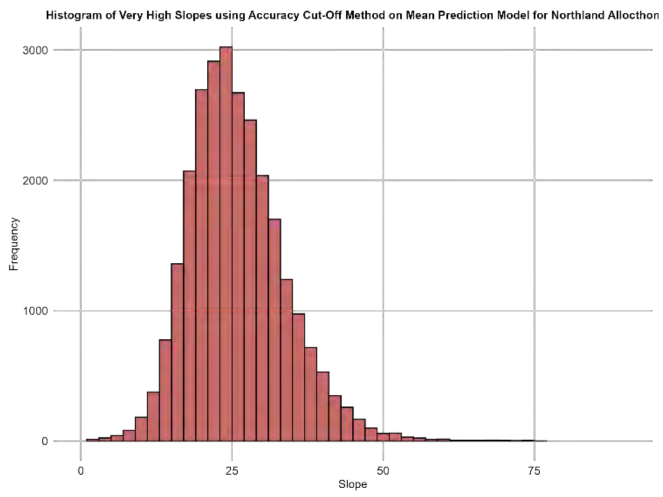


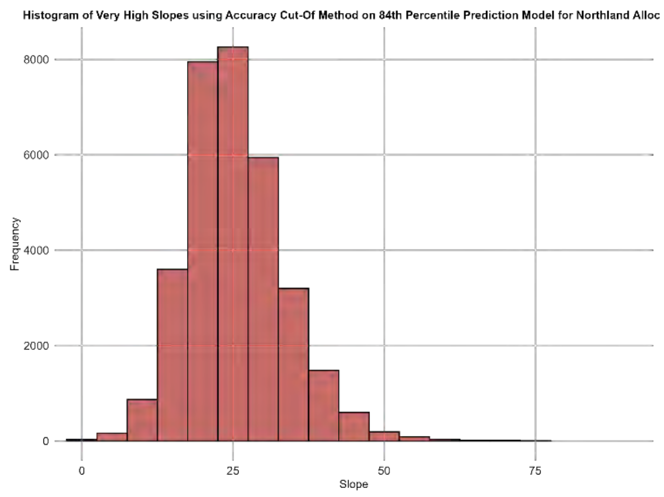
High





Very High



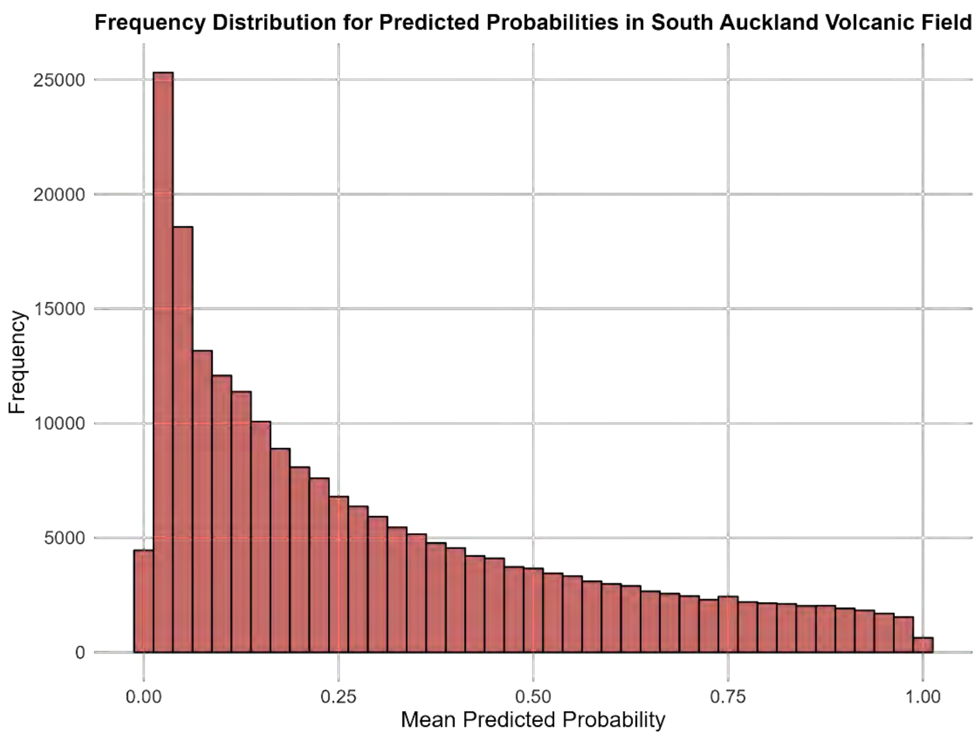


SOUTH AUCKLAND VOLCANIC FIELD

MODEL COEFFICIENTS

Variable	Mean Coefficient	Standard Error	95% Confidence Interval	
			Upper Bound	Lower Bound
Intercept	7.14E+17	7.14E+17	2.11E+18	-6.9E+17
Curvature	-8.6E+10	5.33E+10	1.83E+10	-1.9E+11
GeolUnit4	-7.2E+17	7.16E+17	6.87E+17	-2.1E+18
GeolUnit6	-7.2E+17	7.16E+17	6.87E+17	-2.1E+18
GeolUnit8	-7.7E+17	7.68E+17	7.37E+17	-2.3E+18
GeolUnit11	-7.2E+17	7.16E+17	6.88E+17	-2.1E+18
GeolUnit12	-7.5E+17	7.47E+17	7.17E+17	-2.2E+18
GeolUnit14	-9.7E+17	9.74E+17	9.35E+17	-2.9E+18
DistanceToStream10	2.72E+11	2.73E+11	8.08E+11	-2.6E+11
DistanceToStream20	3.2E+10	3.41E+11	7.01E+11	-6.4E+11
DistanceToStream9999	-3.5E+11	3.7E+11	3.76E+11	-1.1E+12
LCDB2	-7.2E+11	6.56E+11	5.72E+11	-2E+12
LCDB3	-3.4E+11	4.51E+11	5.47E+11	-1.2E+12
LCDB4	5.97E+10	1.52E+11	3.58E+11	-2.4E+11
LCDB5	-1.4E+13	4.05E+12	-6.4E+12	-2.2E+13
LCDB7	3.18E+11	2.25E+11	7.59E+11	-1.2E+11
LocalSlopeRelief	3.5E+11	2.22E+11	7.85E+11	-8.5E+10
Slope	2.94E+11	1.73E+11	6.32E+11	-4.5E+10
OLFP10	1.6E+11	1.59E+11	4.72E+11	-1.5E+11
OLFP9999	-2.9E+10	1.37E+11	2.38E+11	-3E+11
Geomorphon2	1.28E+12	9.91E+11	3.23E+12	-6.6E+11
Geomorphon3	8.07E+11	7.91E+11	2.36E+12	-7.4E+11
Geomorphon4	-5.2E+12	4.16E+12	2.94E+12	-1.3E+13
Geomorphon5	1.33E+12	1.2E+12	3.68E+12	-1E+12
Geomorphon6	1.23E+12	1.24E+12	3.66E+12	-1.2E+12
Geomorphon7	1.31E+12	1.31E+12	3.88E+12	-1.3E+12
Geomorphon8	9.14E+11	1.4E+12	3.66E+12	-1.8E+12
Geomorphon9	1.52E+12	1.43E+12	4.32E+12	-1.3E+12
Geomorphon10	1.75E+12	1.47E+12	4.63E+12	-1.1E+12
Aspect	-1.1E+11	7.87E+10	4.34E+10	-2.7E+11

PROBABILITY DISTRIBUTION



AREA COMPARISONS

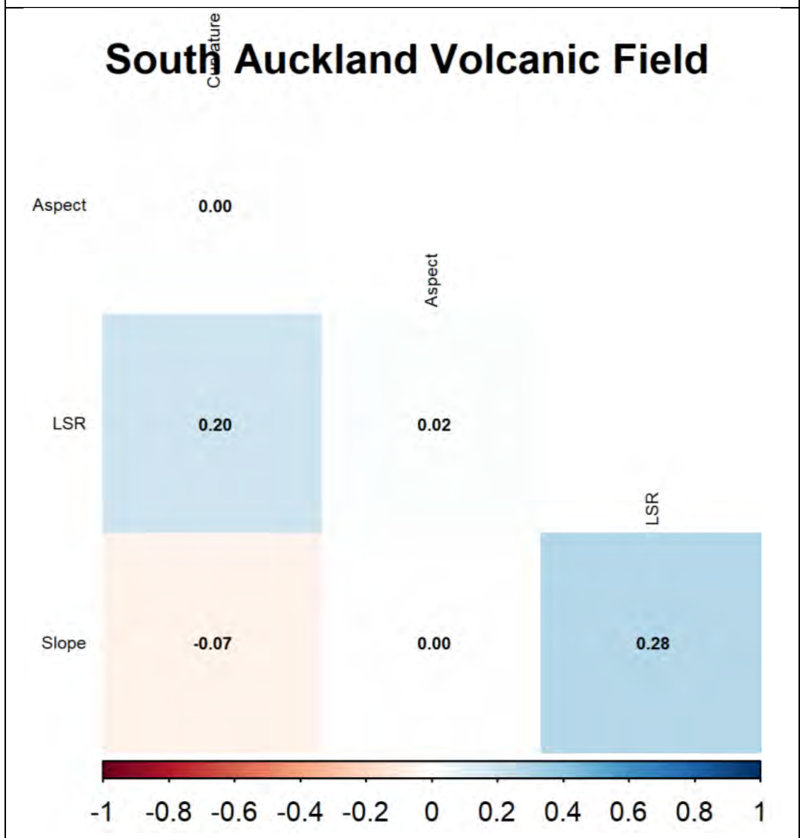
	Land area comparison					
	South Auckland Volcanic Field					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	81.5%	78.6%	75.0%	71.7%	74.9%	71.6%
Low	9.9%	10.9%	6.2%	6.7%	7.6%	8.1%
Moderate	5.5%	6.4%	6.3%	6.8%	6.5%	7.1%
High	3.1%	4.1%	6.2%	7.0%	5.6%	6.4%
Very High			6.3%	7.8%	5.4%	6.8%

	Landslide inventory density (landslide area per class/total landslide area per region)					
	South Auckland Volcanic Field					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	25.2%	14.9%	14.2%	8.8%	14.2%	8.5%
Low	24.7%	22.1%	10.3%	5.7%	13.1%	8.5%
Moderate	25.2%	26.9%	11.8%	11.6%	14.2%	12.0%
High	24.9%	36.1%	23.0%	20.1%	21.2%	21.2%
Very High			40.7%	53.8%	37.2%	49.7%

	Landslide number density (landslide cells/total cells per region)					
	South Auckland Volcanic Field					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
Low	0.5%	0.4%	0.3%	0.2%	0.3%	0.2%
Moderate	0.9%	0.8%	0.4%	0.3%	0.4%	0.3%
High	1.5%	1.7%	0.7%	0.5%	0.7%	0.6%
Very High			1.2%	1.3%	1.3%	1.4%

VARIABLE CORRELATIONS

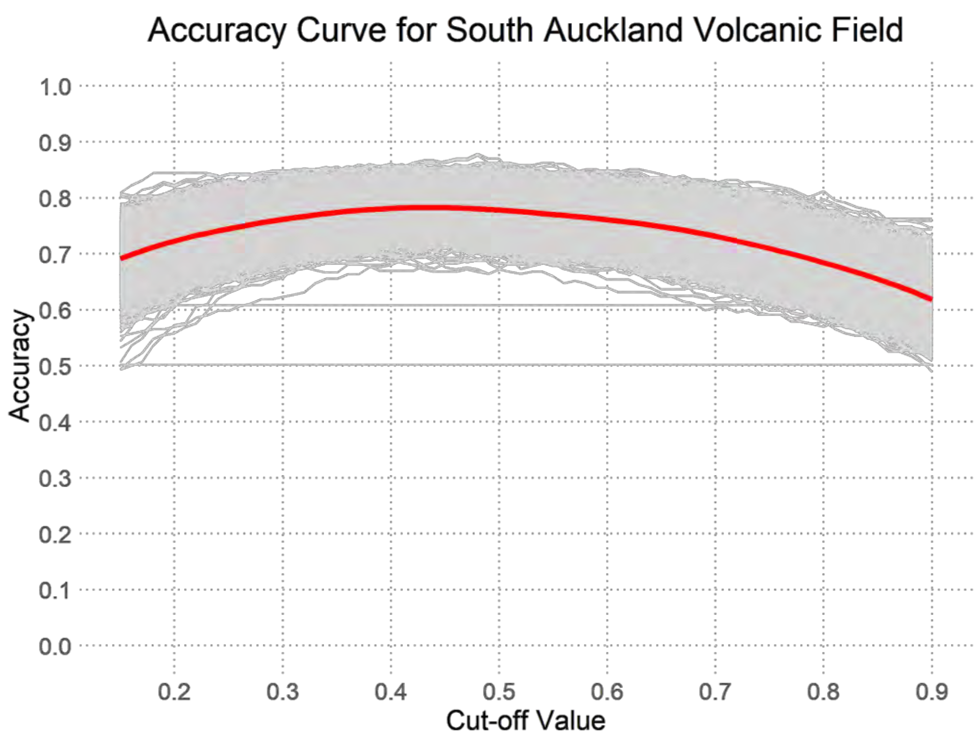
Continuous Variables



Categorical Variables

GeolUnit_vs_Geomorphon	0.124950233
GeolUnit_vs_DistanceToStream	0.041467435
GeolUnit_vs_LCDB	0.123586204
GeolUnit_vs_OLFP	0.046970763
Geomorphon_vs_DistanceToStream	0.243734805
Geomorphon_vs_LCDB	0.104218257
Geomorphon_vs_OLFP	0.243137710
DistanceToStream_vs_LCDB	0.074226600
DistanceToStream_vs_OLFP	0.146660190
LCDB_vs_OLFP	0.032064501

ACCURACY PLOT



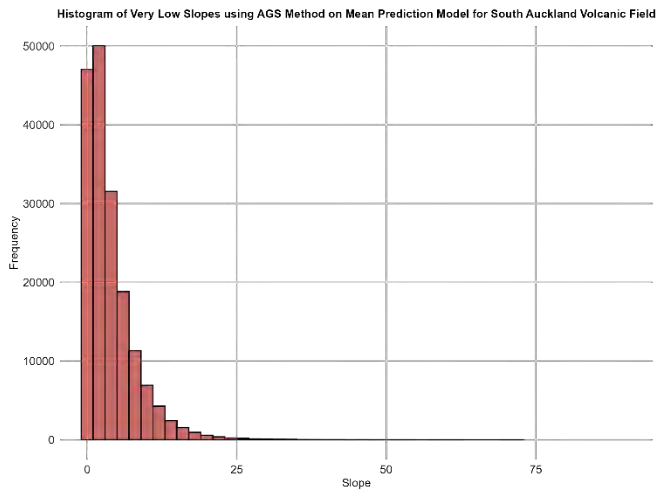
SLOPE ANGLE DISTRIBUTIONS

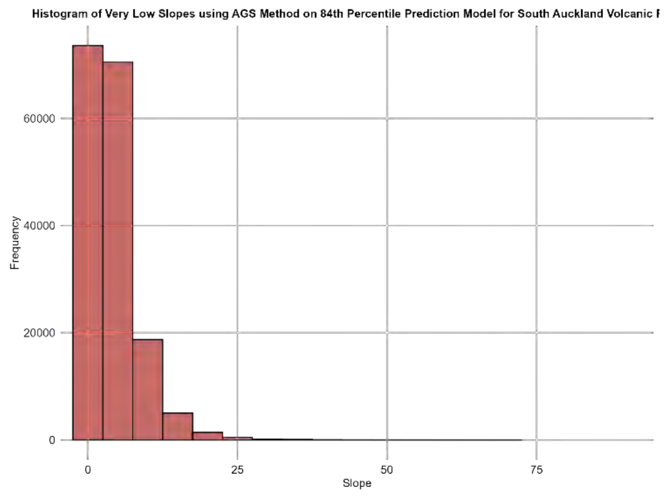
METHOD 1 (AGS)

Mean predictions

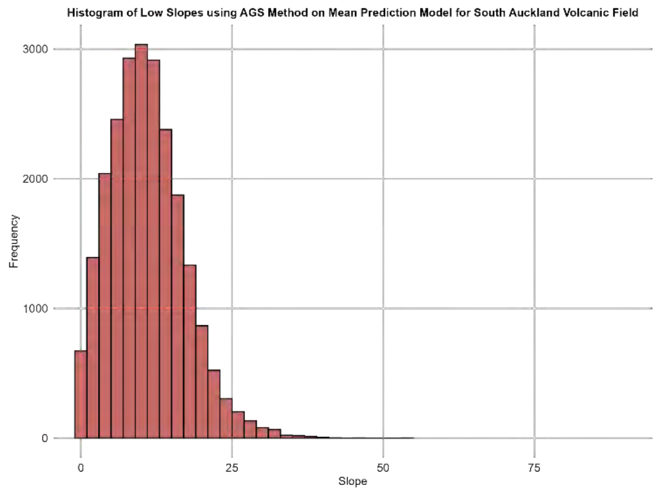
84th percentile predictions

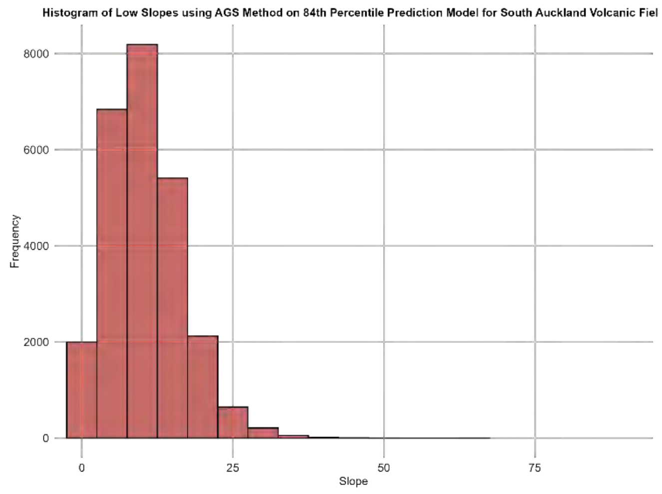
Very Low



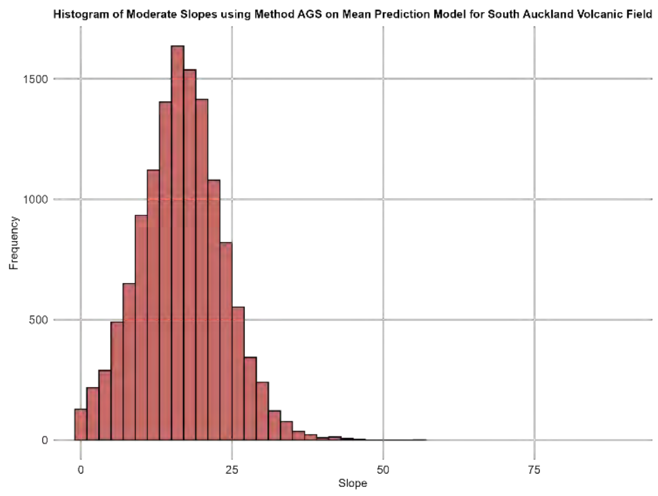


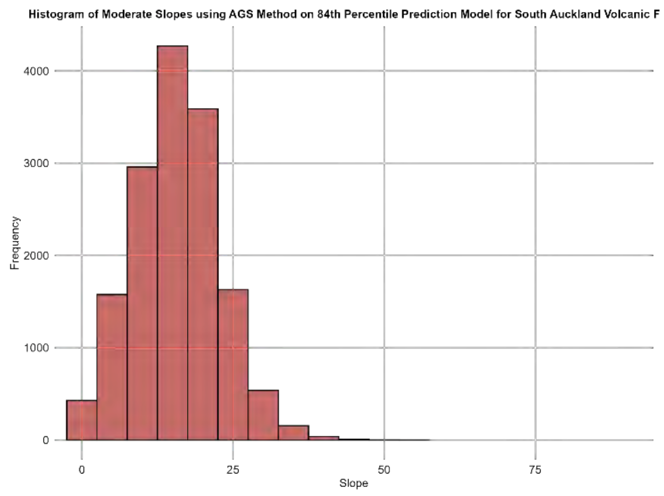
Low



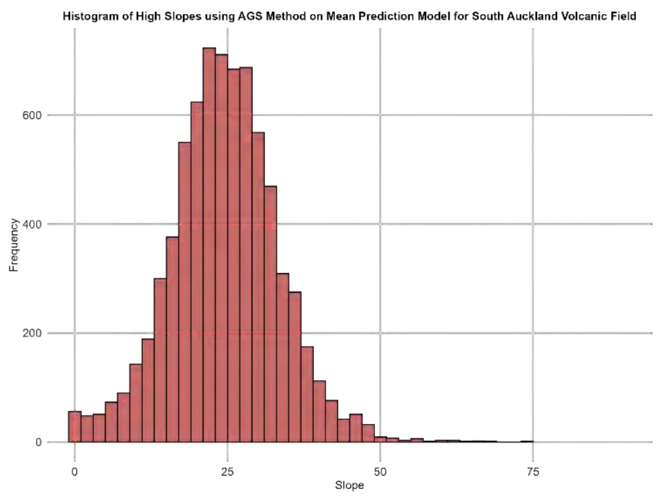


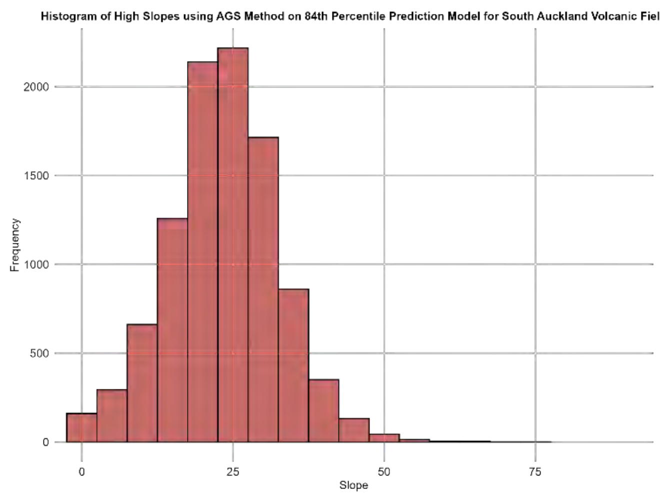
Moderate





High

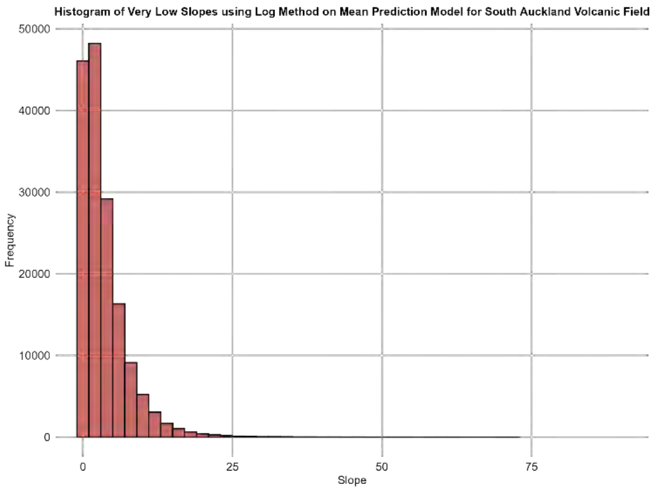


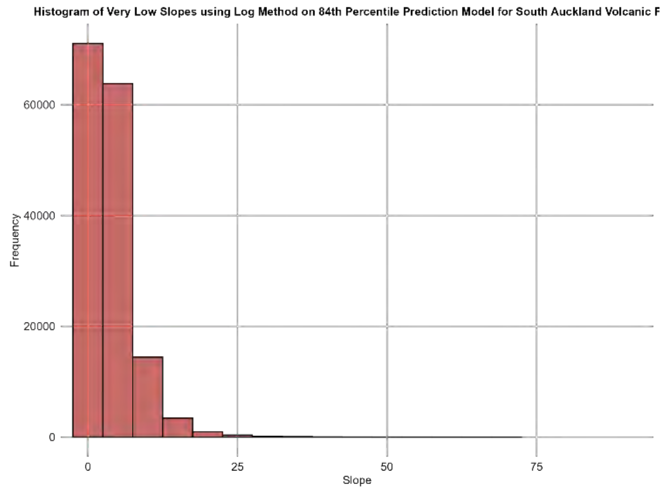


METHOD 2 (LOG BINS)

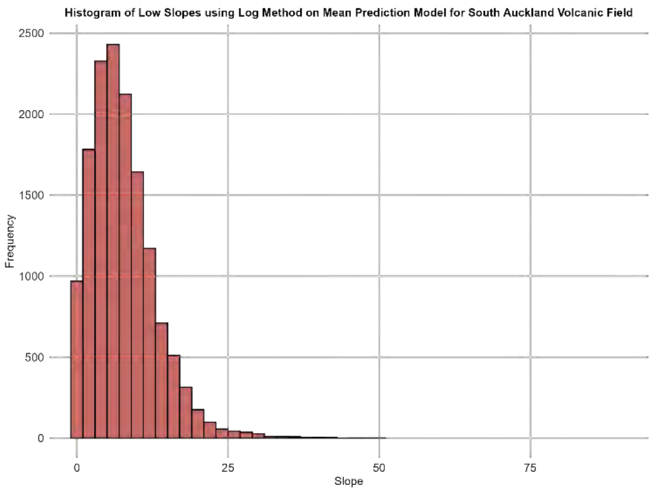
Mean predictions | 84th percentile predictions

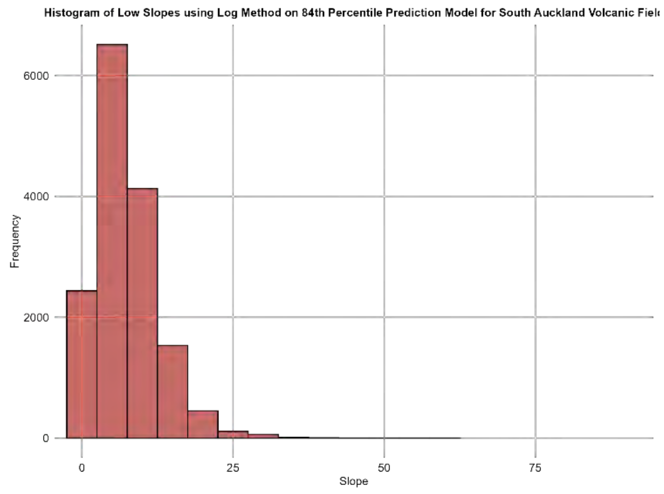
Very Low



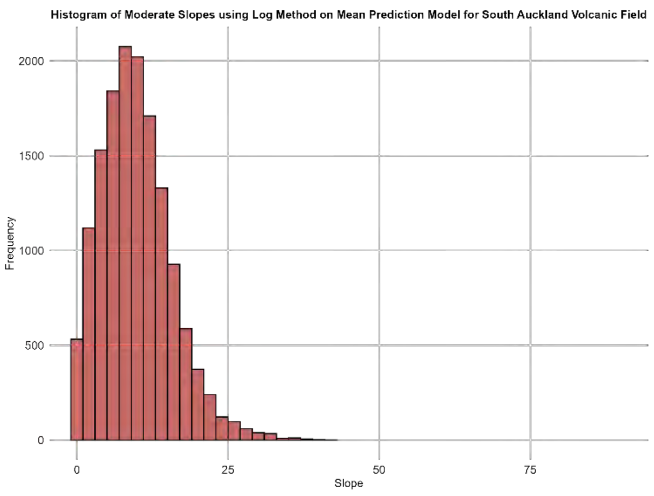


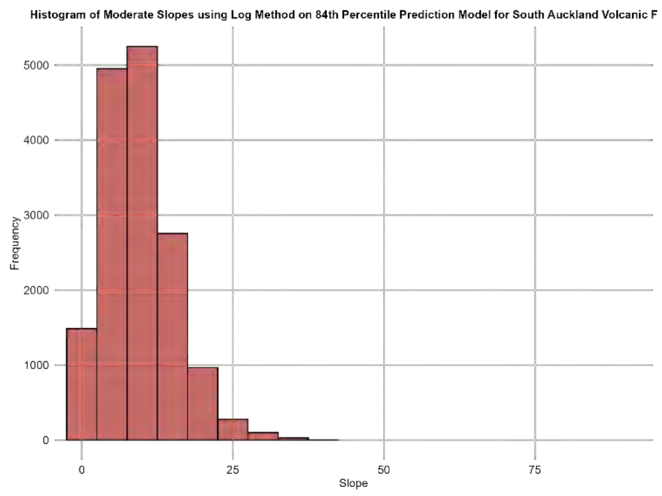
Low



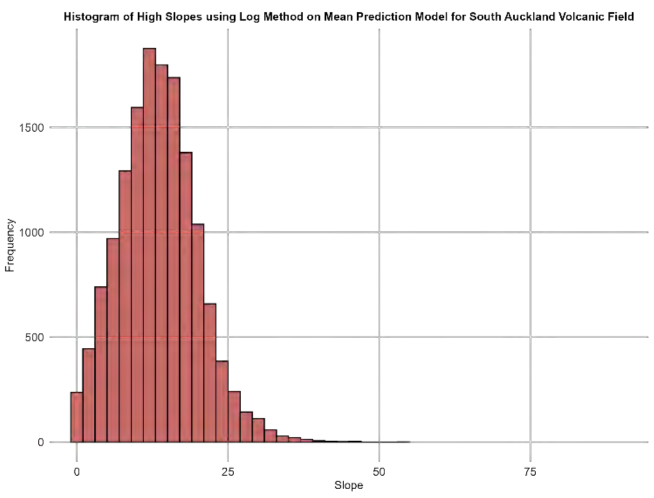


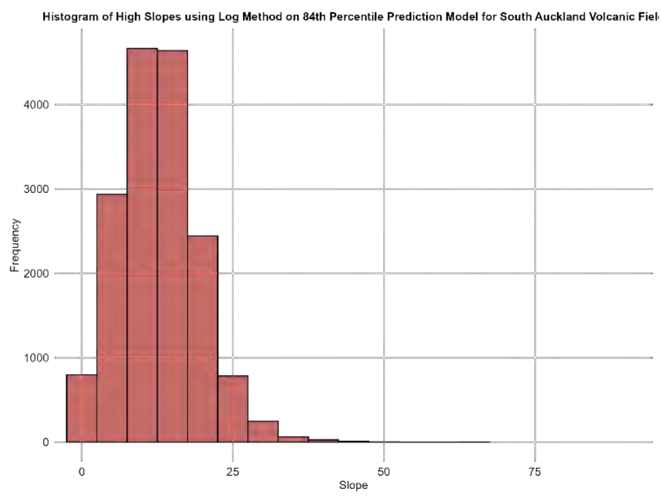
Moderate



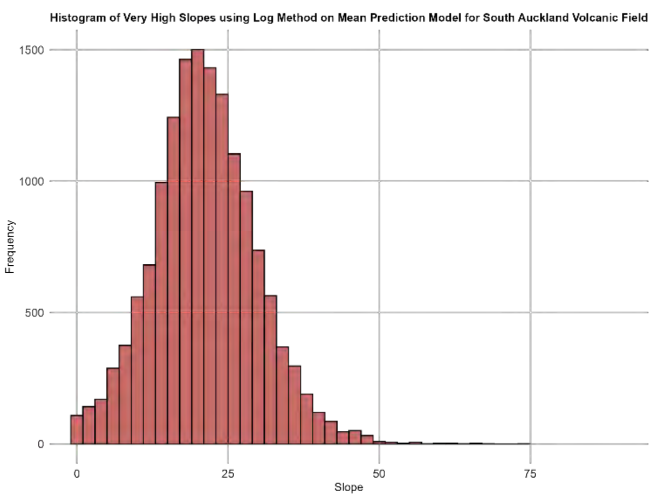


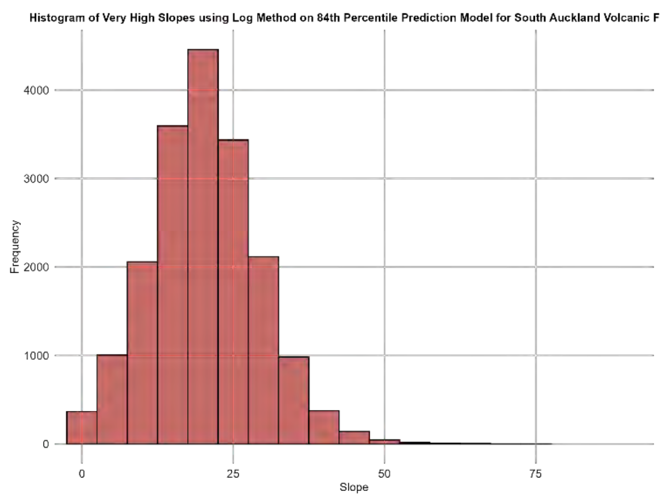
High





Very High

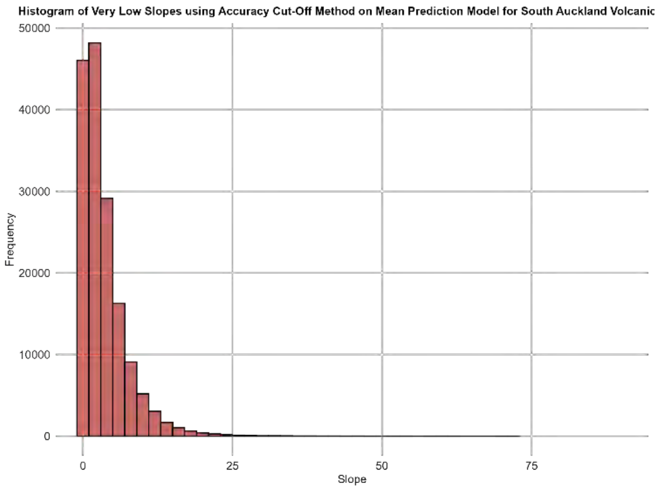


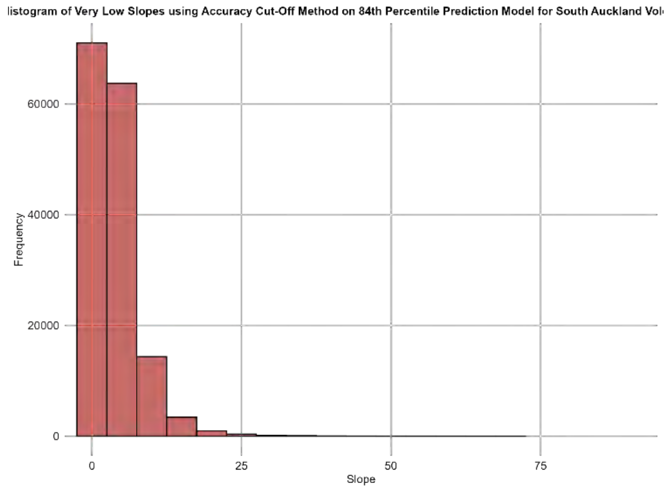


METHOD 3 (ACCURACY CUT-OFF)

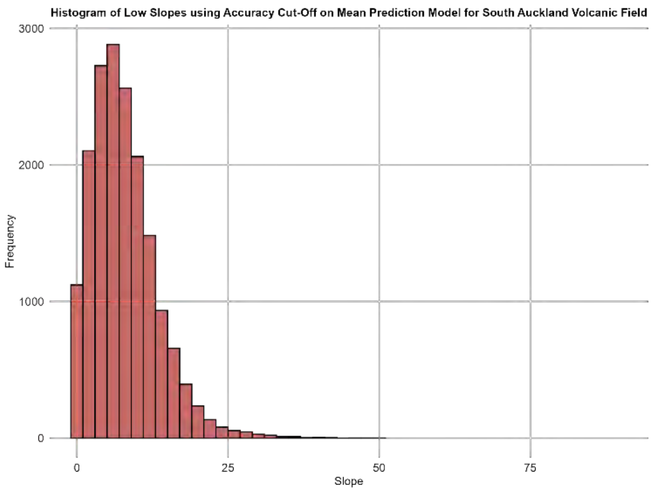
Mean predictions | 84th percentile predictions

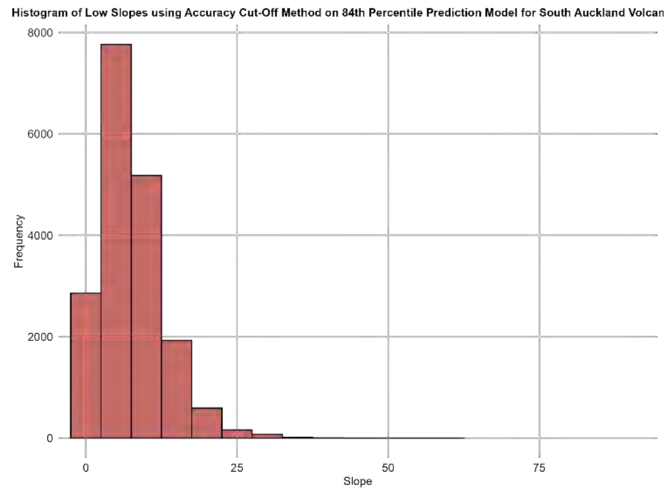
Very Low



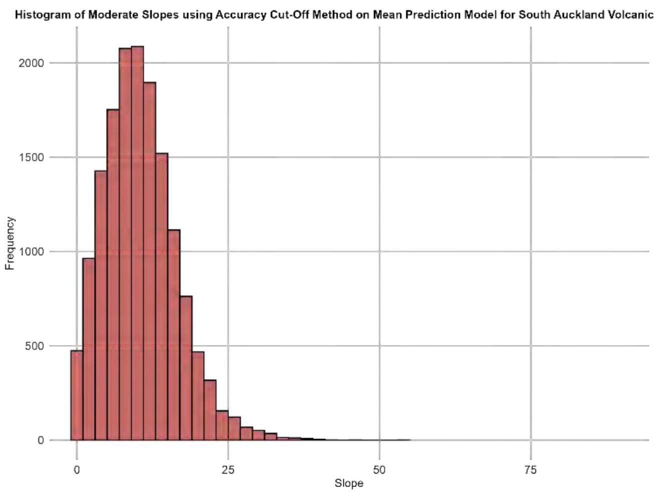


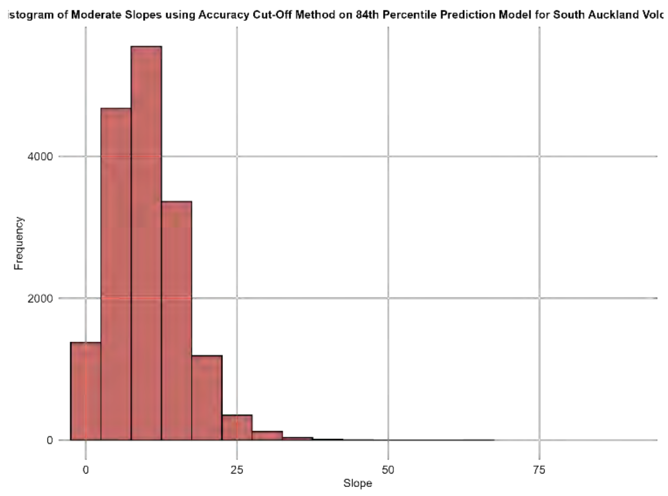
Low



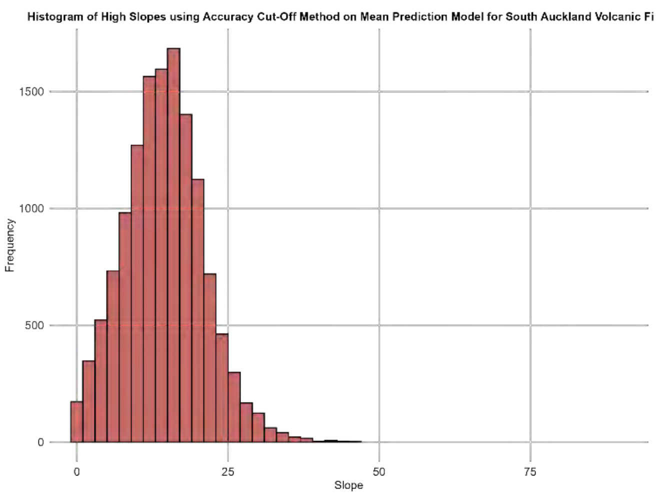


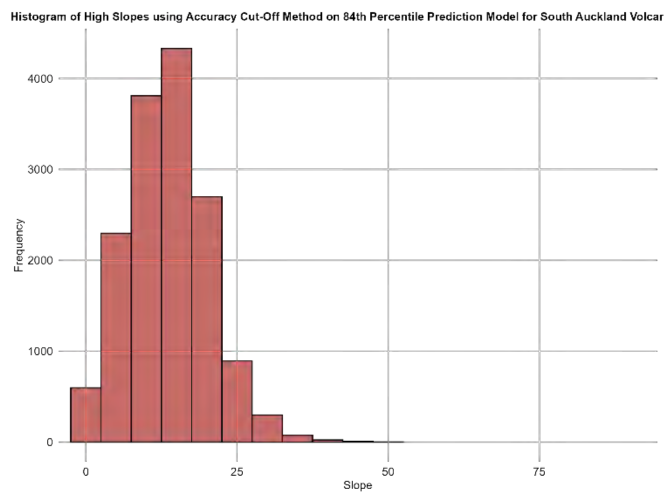
Moderate



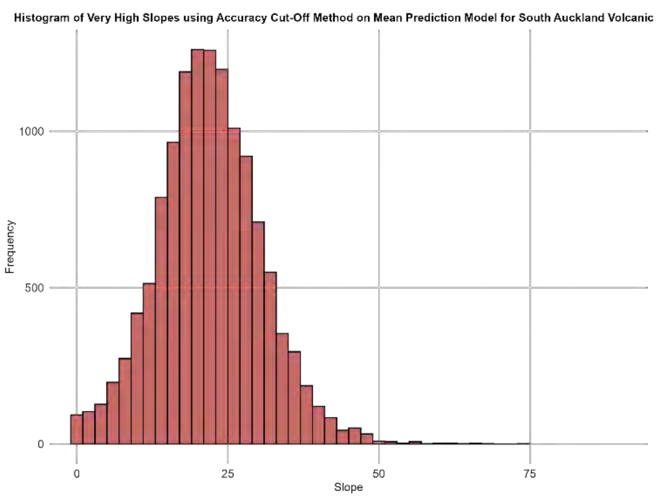


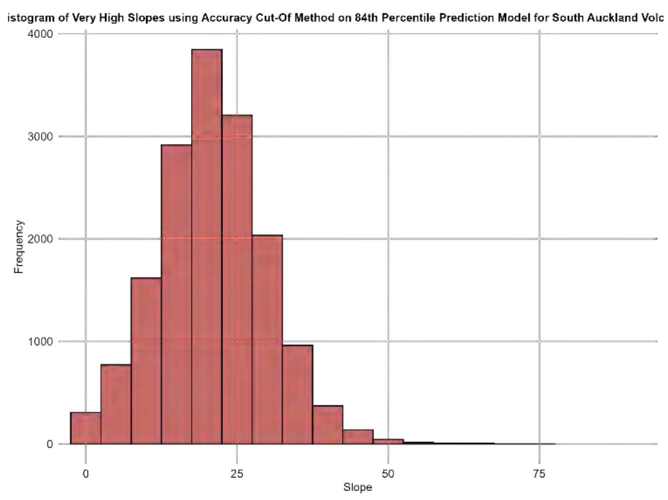
High





Very High



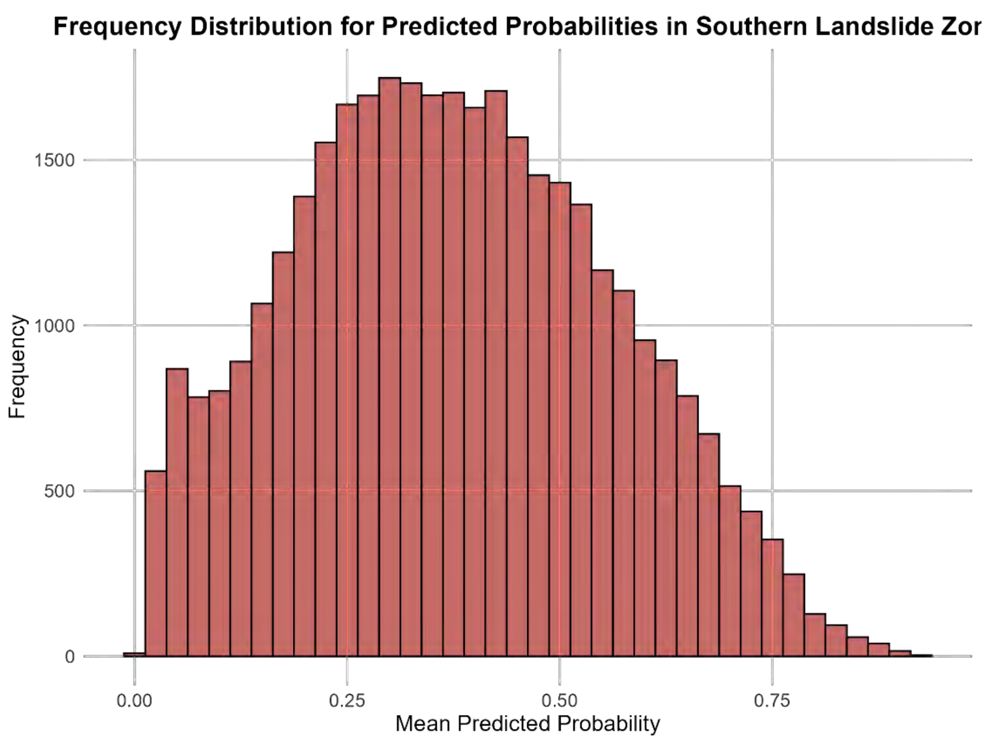


SOUTHERN LANDSLIDE ZONE

MODEL COEFFICIENTS

Variable	Mean Coefficient	Standard Error	95% Confidence Interval	
			Upper Bound	Lower Bound
Intercept	-2.29562	0.002785	-2.29017	-2.30108
Aspect	-0.05659	0.000157	-0.05628	-0.0569
Curvature	-0.00809	0.000139	-0.00782	-0.00836
GeolUnit3	-0.62369	0.00368	-0.61648	-0.63091
GeolUnit4	-0.86291	0.002194	-0.85861	-0.86721
GeolUnit5	-1.51722	0.007328	-1.50285	-1.53158
GeolUnit6	0.182471	0.004926	0.192128	0.172814
GeolUnit7	1.581133	0.00378	1.588543	1.573722
GeolUnit8	1.330854	0.002132	1.335034	1.326674
GeolUnit9	0.017074	0.002913	0.022784	0.011363
GeolUnit10	1.040396	0.003775	1.047796	1.032996
GeolUnit11	-7.96754	0.064685	-7.84054	-8.09455
GeolUnit12	-0.16999	0.007384	-0.15551	-0.18446
GeolUnit13	0.806989	0.00228	0.811459	0.80252
GeolUnit14	-8.65192	0.017188	-8.61822	-8.68563
Geomorphon1	-1.60313	0.003232	-1.5968	-1.60947
Geomorphon3	0.075689	0.001234	0.078108	0.07327
Geomorphon4	-0.85586	0.002631	-0.8507	-0.86102
Geomorphon5	0.16616	0.001225	0.168561	0.163759
Geomorphon6	0.434274	0.001243	0.436712	0.431837
Geomorphon7	0.68945	0.001327	0.692051	0.686848
Geomorphon8	-0.43139	0.002012	-0.42745	-0.43534
Geomorphon9	0.695463	0.001386	0.69818	0.692745
Geomorphon10	1.172883	0.001863	1.176536	1.169231
DistanceToStream10	-0.01891	0.001819	-0.01535	-0.02248
DistanceToStream20	0.008284	0.001529	0.011282	0.005287
DistanceToStream9999	-0.19249	0.001331	-0.18988	-0.1951
LCDB0	1.039046	0.001725	1.042428	1.035664
LCDB2	-0.81461	0.00075	-0.81314	-0.81608
LCDB3	0.460985	0.001423	0.463775	0.458195
LCDB4	0.995748	0.000379	0.99649	0.995006
LCDB5	0.79105	0.003129	0.797184	0.784916
LCDB7	0.905426	0.001466	0.908299	0.902553
LocalSlopeRelief	0.428646	0.00026	0.429155	0.428137
Slope	0.659952	0.00021	0.660364	0.65954
OLFP10	-0.05765	0.000675	-0.05633	-0.05898
OLFP9999	0.143132	0.000523	0.144157	0.142108

PROBABILITY DISTRIBUTION



AREA COMPARISONS

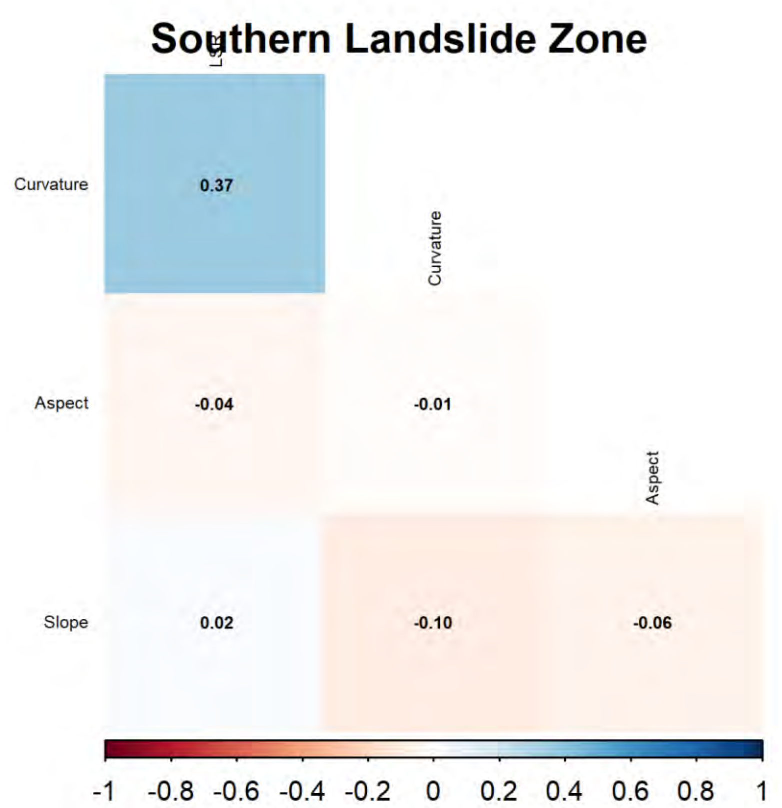
	Land area comparison					
	Southern Landslide Zone					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	10.9%	10.1%	75.0%	72.4%	35.4%	33.0%
Low	29.1%	27.4%	6.2%	6.8%	41.2%	41.1%
Moderate	42.8%	43.4%	6.2%	6.6%	10.7%	11.4%
High	17.1%	19.1%	6.3%	6.8%	8.3%	9.3%
Very High			6.3%	7.4%	4.3%	5.2%

	Landslide inventory density (landslide area per class/total landslide area per region)					
	Southern Landslide Zone					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	1.0%	0.9%	37.3%	34.4%	8.0%	7.2%
Low	9.1%	7.7%	8.7%	7.5%	30.7%	28.8%
Moderate	39.9%	36.3%	12.8%	12.8%	20.0%	18.3%
High	50.0%	55.1%	20.0%	19.9%	24.0%	26.5%
Very High			21.1%	25.3%	17.3%	19.2%

	Landslide number density (landslide cells/total cells per region)					
	Southern Landslide Zone					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	0.2%	0.1%	0.8%	0.8%	0.4%	0.4%
Low	0.5%	0.5%	2.3%	1.8%	1.2%	1.1%
Moderate	1.5%	1.4%	3.3%	3.1%	3.0%	2.6%
High	4.7%	4.7%	5.2%	4.8%	4.6%	4.6%
Very High			5.5%	5.5%	6.4%	6.0%

VARIABLE CORRELATIONS

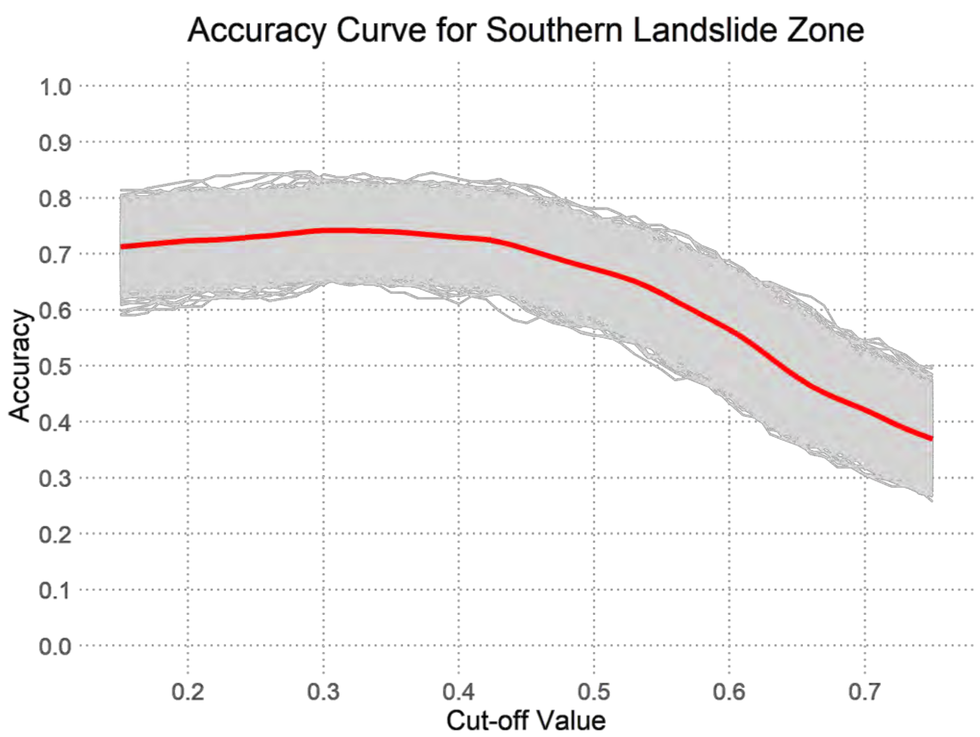
Continuous Variables



Categorical Variables

GeolUnit_vs_Geomorphon	0.067785649
GeolUnit_vs_DistanceToStream	0.034737223
GeolUnit_vs_LCDB	0.054513004
GeolUnit_vs_OLFP	0.016327665
Geomorphon_vs_DistanceToStream	0.235646634
Geomorphon_vs_LCDB	0.189041525
Geomorphon_vs_OLFP	0.310693768
DistanceToStream_vs_LCDB	0.090863148
DistanceToStream_vs_OLFP	0.158985060
LCDB_vs_OLFP	0.085121101

ACCURACY PLOT

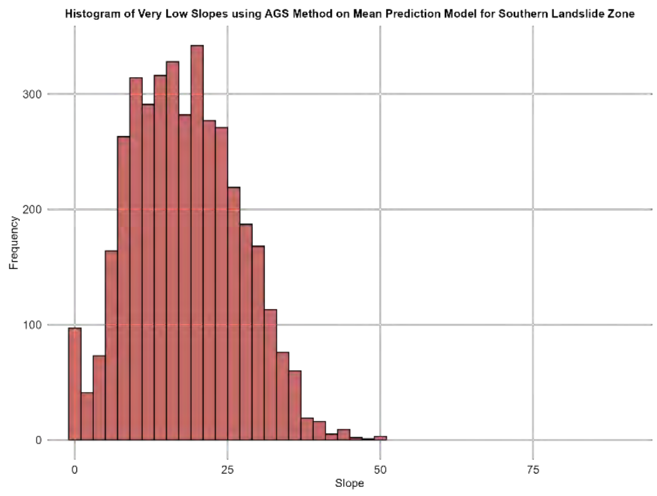


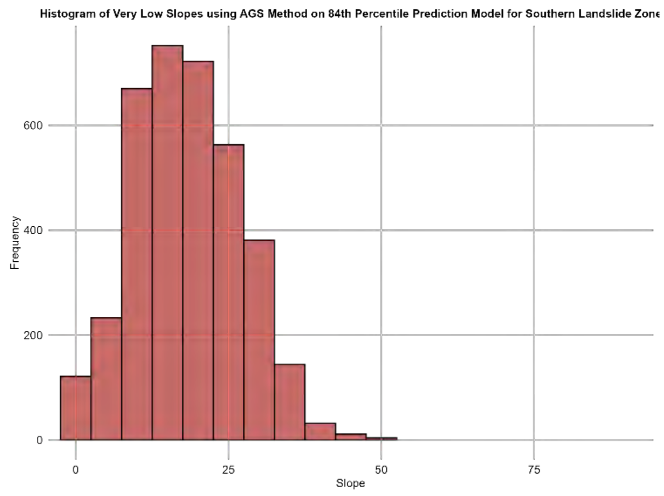
SLOPE ANGLE DISTRIBUTIONS

METHOD 1 (AGS)

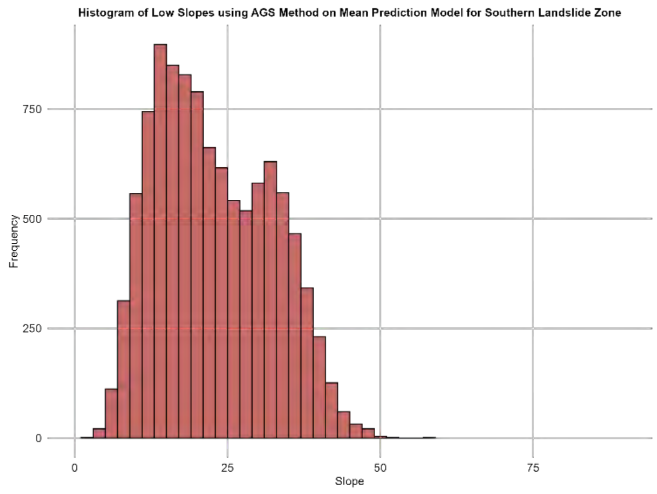
Mean predictions | 84th percentile predictions

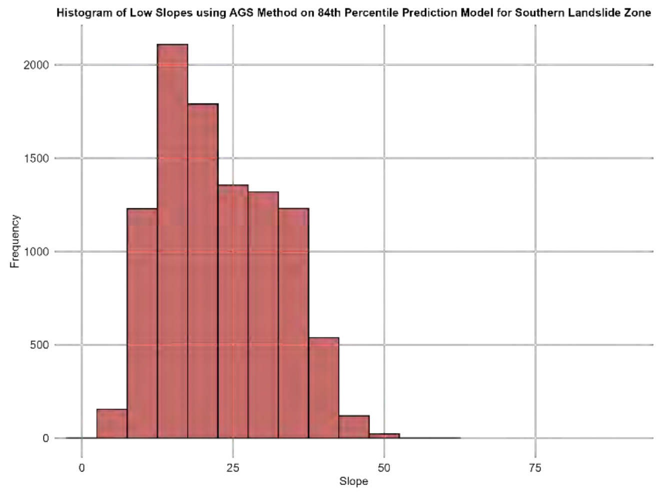
Very Low



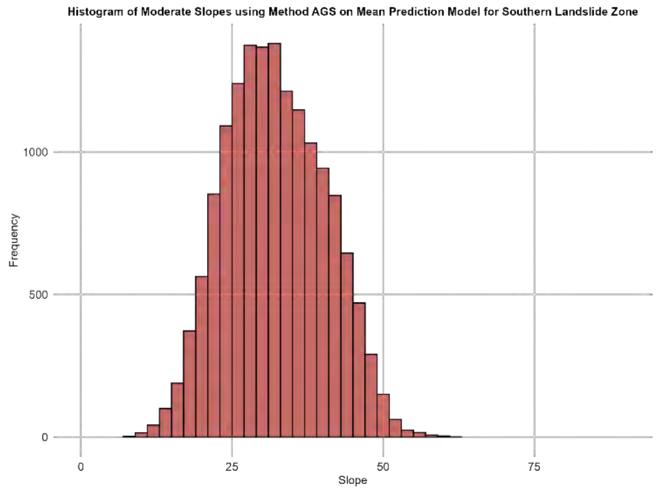


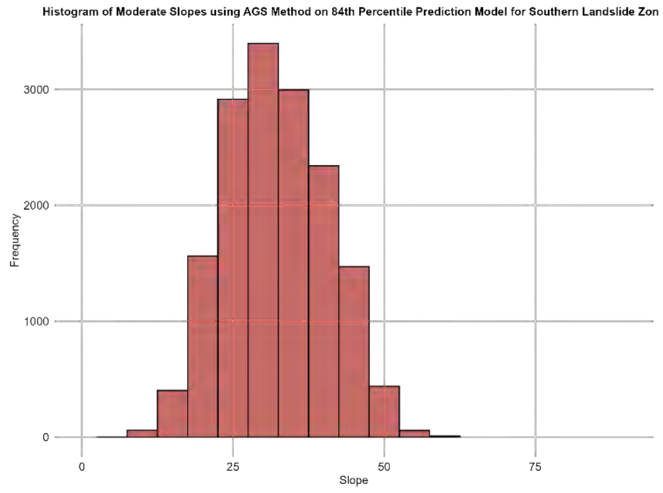
Low



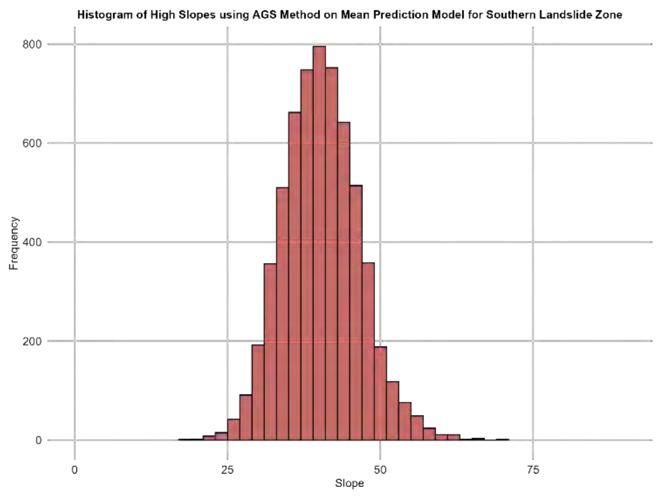


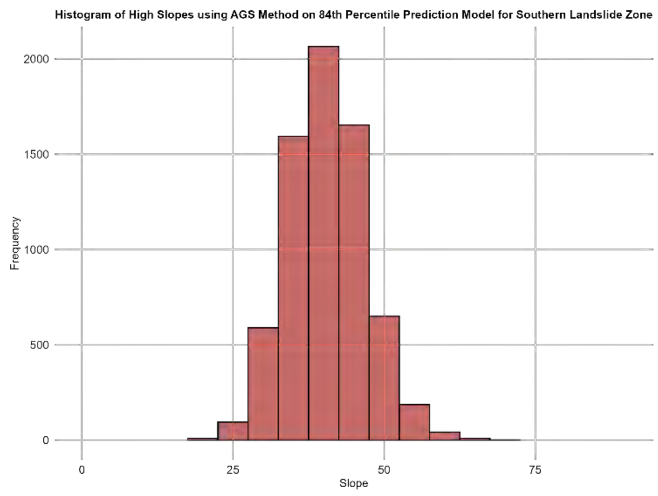
Moderate





High

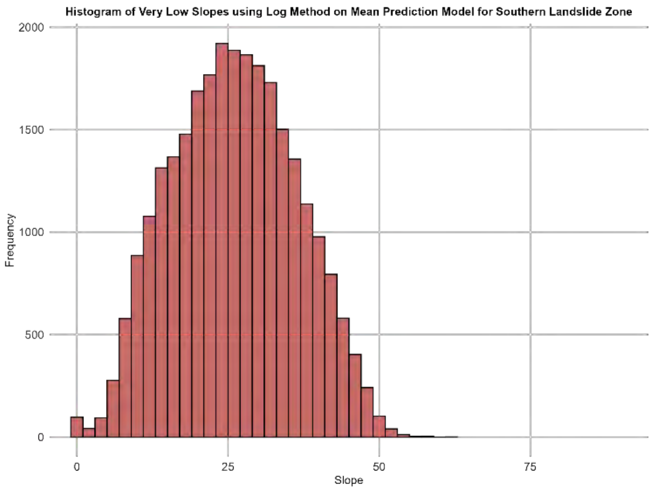


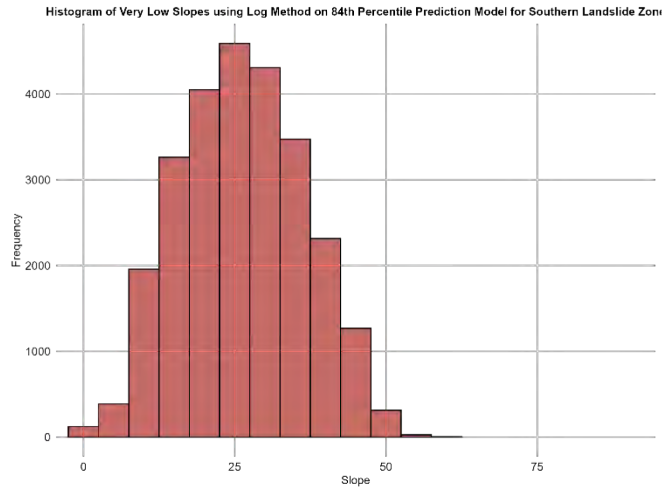


METHOD 2 (LOG BINS)

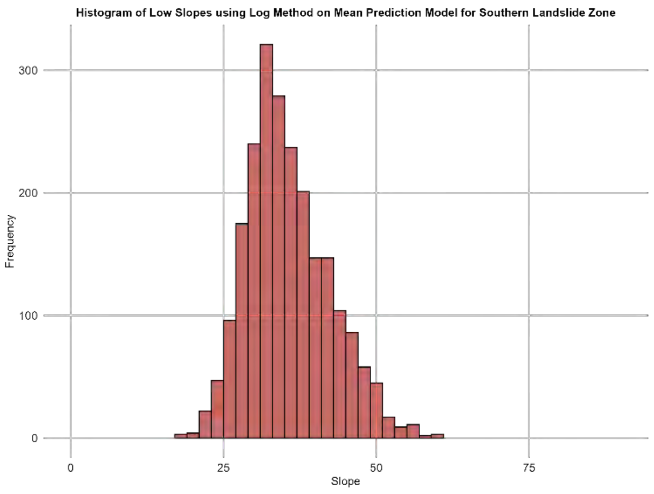
Mean predictions | 84^{th} percentile predictions

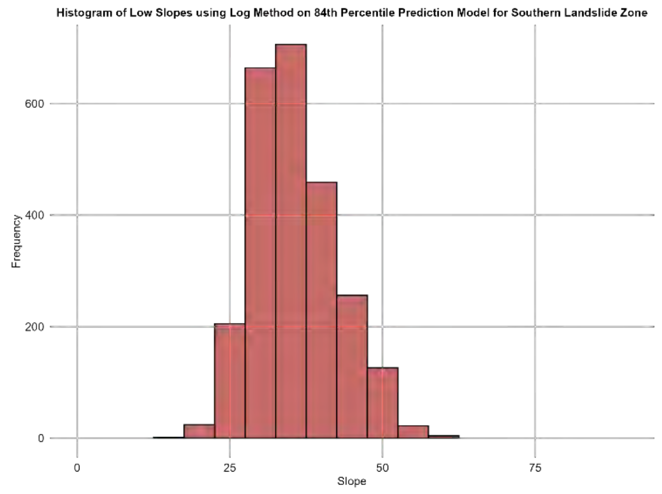
Very Low



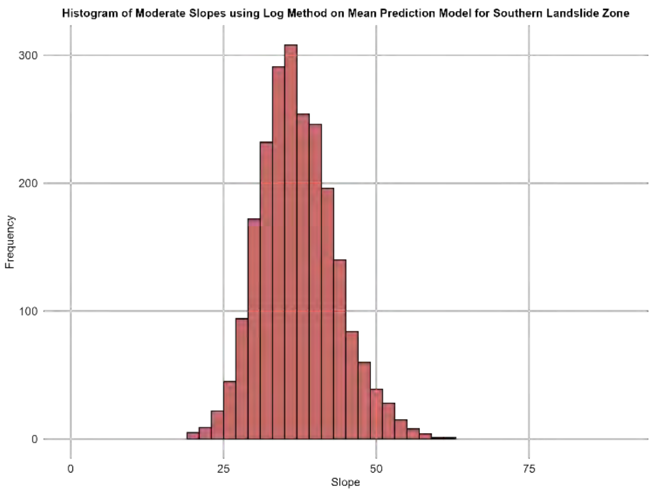


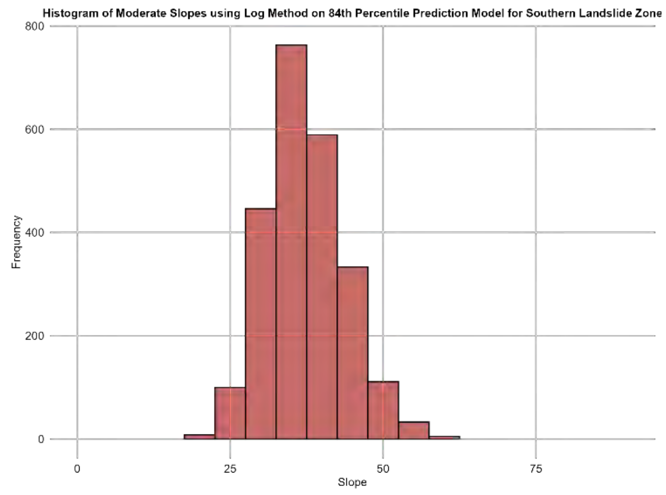
Low



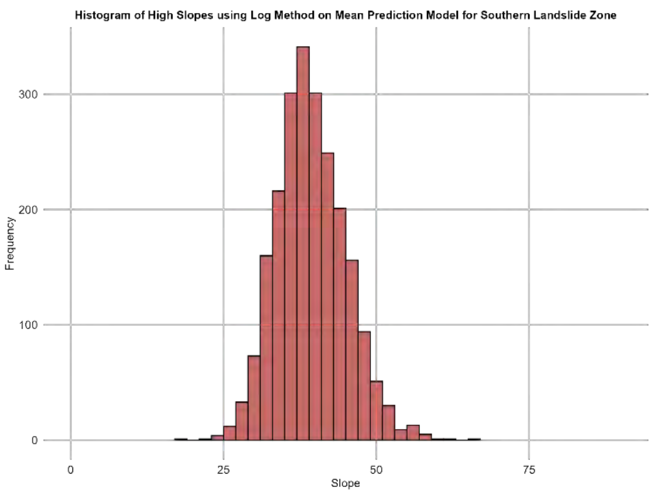


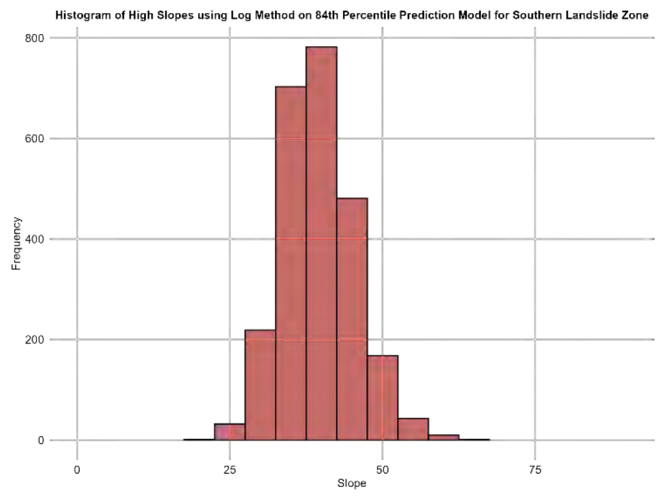
Moderate



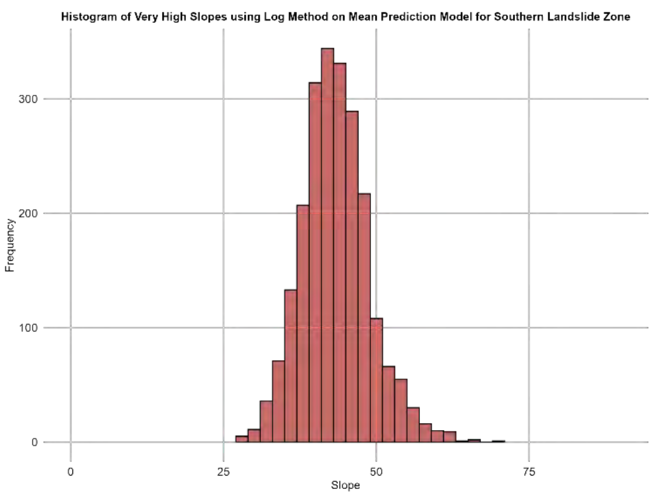


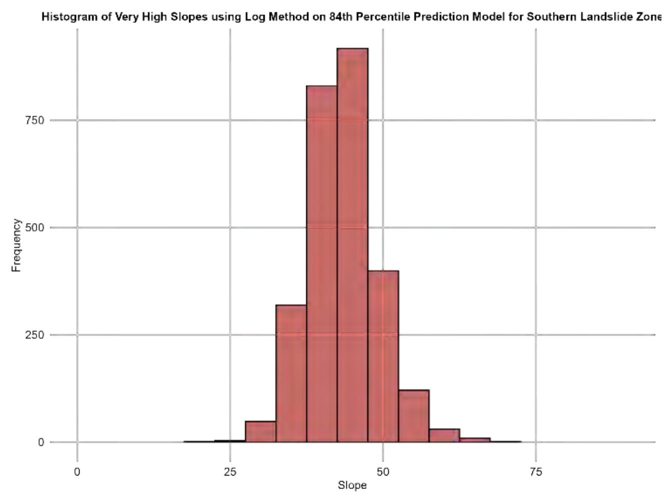
High





Very High



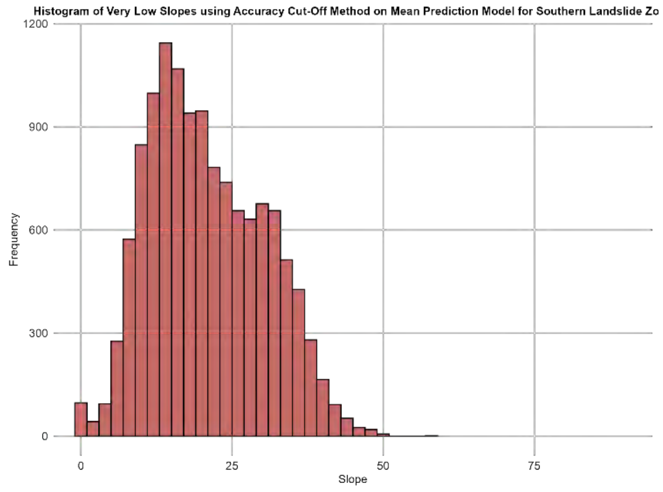


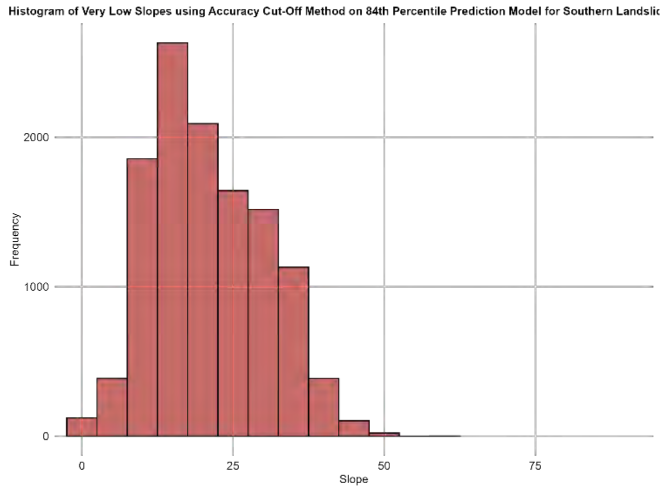
METHOD 3 (ACCURACY CUT-OFF)

Mean predictions

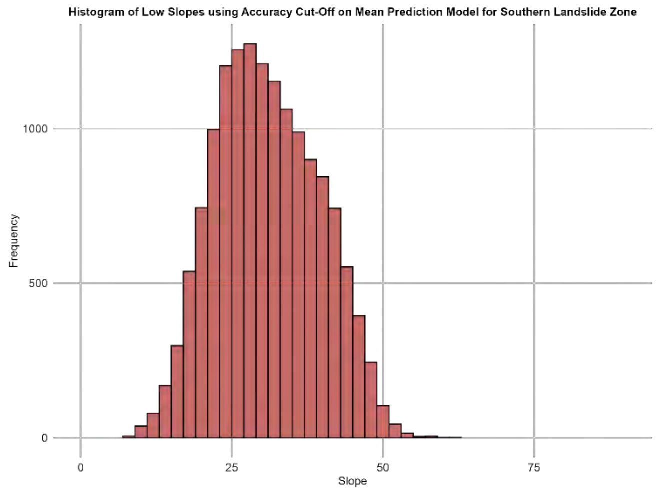
84th percentile predictions

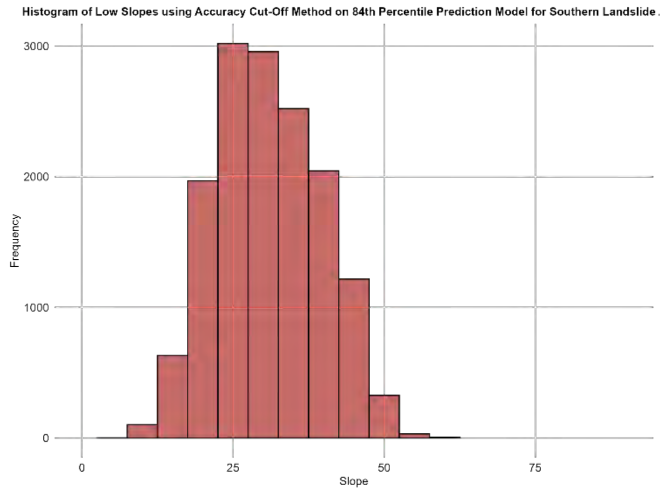
Very Low



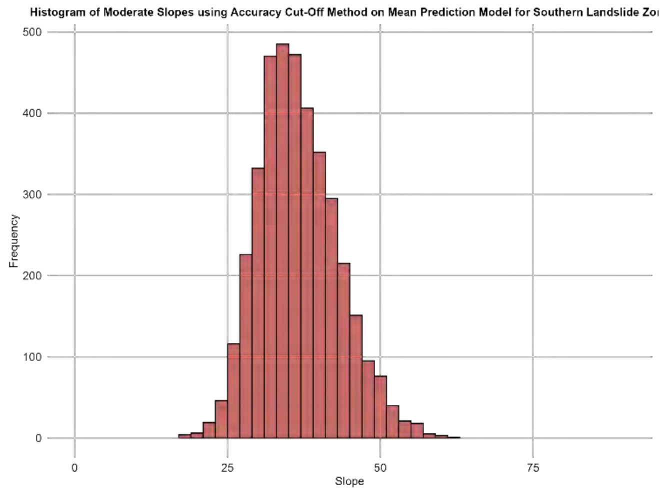


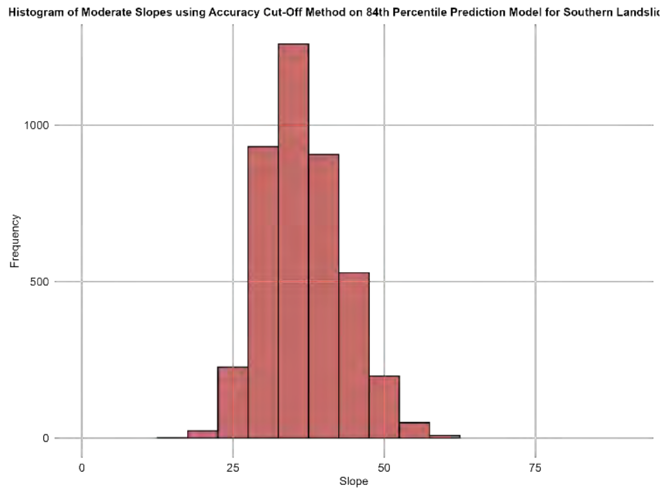
Low



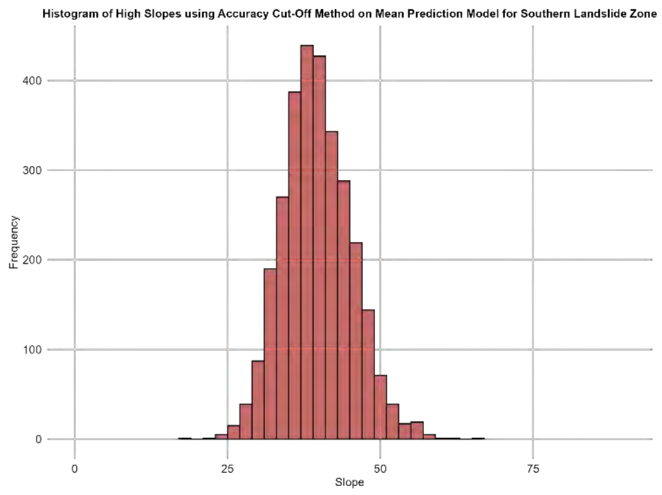


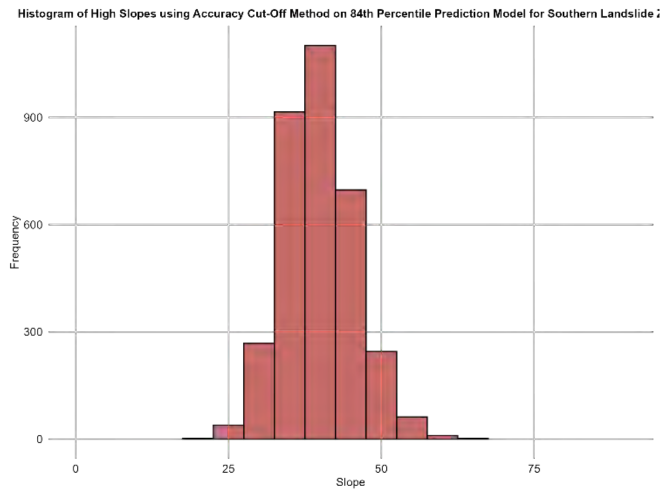
Moderate



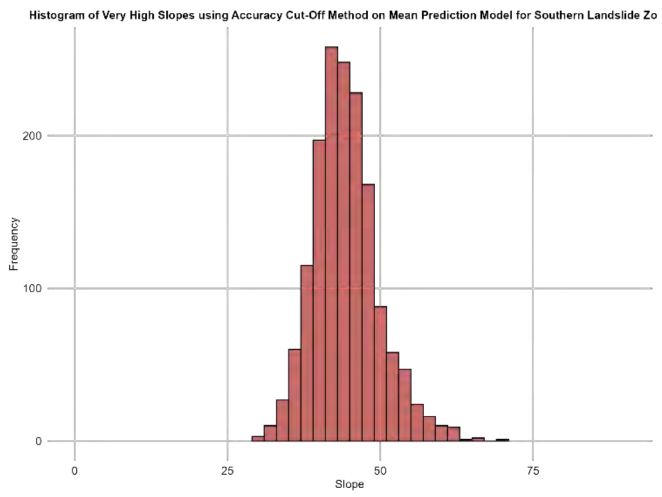


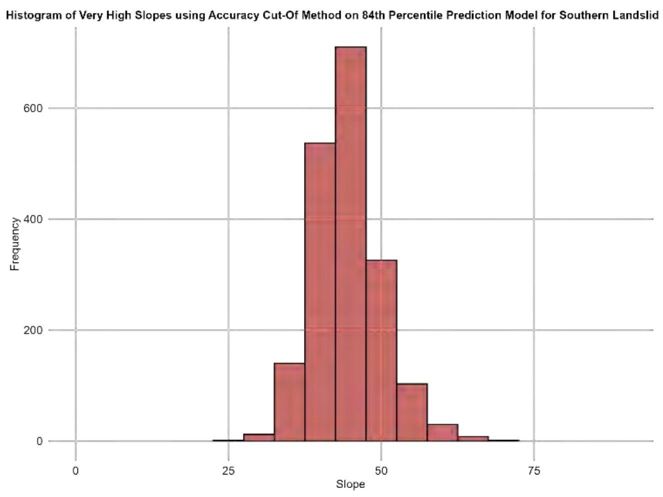
High





Very High



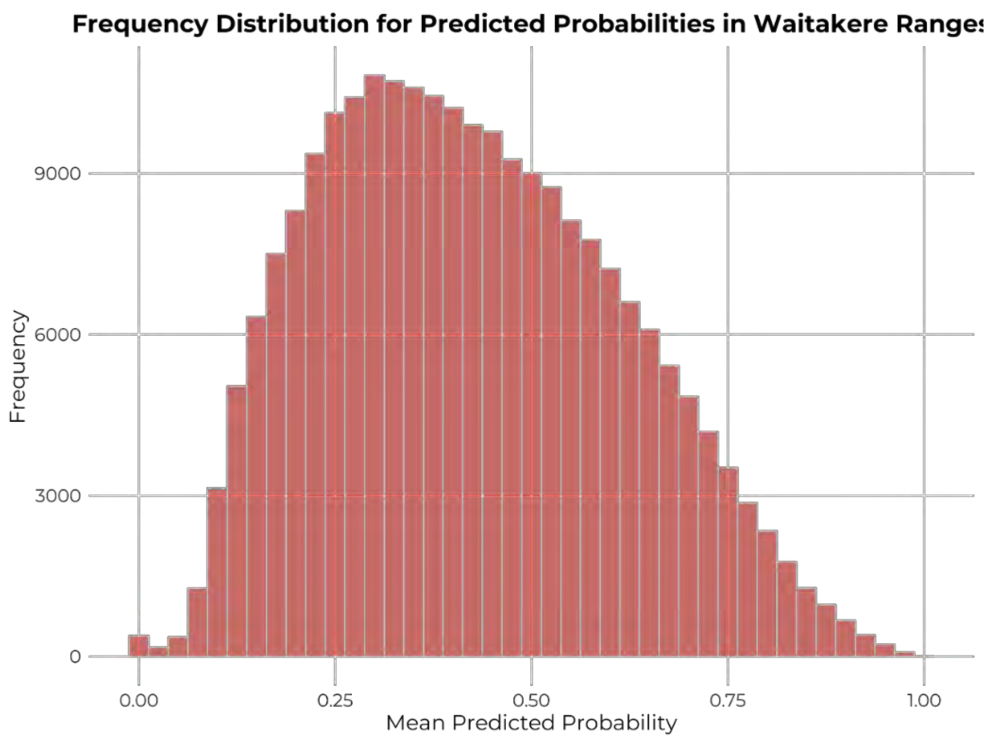


WAITAKERE RANGES

MODEL COEFFICIENTS

Variable	Mean Coefficient	Standard Error	95% Confidence Interval	
			Upper Bound	Lower Bound
Intercept	-6.1E+11	6.1E+11	5.86E+11	-1.8E+12
Aspect	-1.3E+10	1.29E+10	1.24E+10	-3.8E+10
Curvature	1.52E+10	1.52E+10	4.49E+10	-1.5E+10
Geomorphon2	-2.3E+11	2.26E+11	2.17E+11	-6.7E+11
Geomorphon3	-1.8E+11	1.85E+11	1.77E+11	-5.5E+11
Geomorphon4	-1.2E+12	1.16E+12	1.11E+12	-3.4E+12
Geomorphon5	-1.4E+11	1.37E+11	1.32E+11	-4.1E+11
Geomorphon6	1.07E+11	1.07E+11	3.16E+11	-1E+11
Geomorphon7	-3.8E+10	3.85E+10	3.69E+10	-1.1E+11
Geomorphon8	5.91E+11	5.91E+11	1.75E+12	-5.7E+11
Geomorphon9	1.42E+11	1.42E+11	4.21E+11	-1.4E+11
Geomorphon10	4.19E+11	4.19E+11	1.24E+12	-4E+11
LCDB1	9.82E+11	9.82E+11	2.91E+12	-9.4E+11
LCDB2	1.09E+12	1.09E+12	3.23E+12	-1E+12
LCDB3	6.68E+10	6.68E+10	1.98E+11	-6.4E+10
LCDB4	1.17E+12	1.17E+12	3.45E+12	-1.1E+12
LCDB5	8.69E+11	8.69E+11	2.57E+12	-8.4E+11
LCDB7	7.898953	0.121911	8.137997	7.659909
LocalSlopeRelief	8.32E+10	8.32E+10	2.46E+11	-8E+10
Slope	5.82E+10	5.82E+10	1.72E+11	-5.6E+10
OLFP10	-1E+10	1.03E+10	9.87E+09	-3E+10
OLFP9999	-7.2E+10	7.16E+10	6.88E+10	-2.1E+11
GeolUnit4	7.319379	0.61123	8.523339	6.11542
GeolUnit5	-16.5094	0.16976	-16.0941	-16.9248
GeolUnit8	2.076356	0.420499	2.904626	1.248086
GeolUnit9	4.17015	1.572771	7.319571	1.02073
DistanceToStream10	0.067106	0.016261	0.099041	0.035172
DistanceToStream20	-0.1564	0.01341	-0.13006	-0.18273
DistanceToStream9999	0.172066	0.01241	0.196439	0.147694

PROBABILITY DISTRIBUTION



AREA COMPARISONS

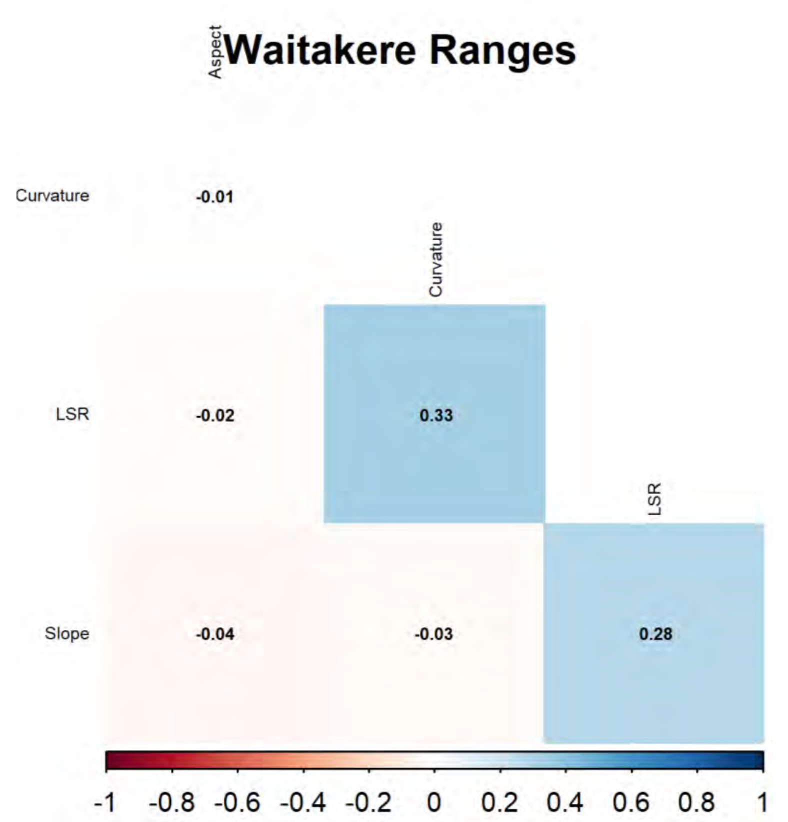
	Land area comparison					
	Waitakere Ranges					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	7.1%	4.7%	75.0%	71.2%	29.5%	24.8%
Low	32.0%	29.4%	6.2%	6.7%	33.3%	33.4%
Moderate	41.2%	42.6%	6.3%	6.9%	15.1%	16.0%
High	19.8%	23.2%	6.3%	7.2%	13.0%	14.4%
Very High			6.3%	8.0%	9.1%	11.4%

	Landslide inventory density (landslide area per class/total landslide area per region)					
	Waitakere Ranges					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	1.0%	0.4%	42.0%	36.0%	6.9%	4.8%
Low	9.0%	7.3%	9.9%	9.4%	21.1%	17.8%
Moderate	40.0%	36.1%	13.7%	12.9%	19.0%	16.5%
High	50.0%	56.2%	15.2%	16.7%	25.7%	27.4%
Very High			19.2%	25.0%	27.3%	33.4%

	Landslide number density (landslide cells/total cells per region)					
	Waitakere Ranges					
	AGS		Log		Accuracy	
	Mean	84th	Mean	84th	Mean	84th
Very Low	0.1%	0.1%	0.4%	0.4%	0.2%	0.2%
Low	0.2%	0.2%	1.3%	1.1%	0.5%	0.4%
Moderate	0.8%	0.7%	1.8%	1.5%	1.0%	0.8%
High	2.0%	1.9%	1.9%	1.9%	1.6%	1.5%
Very High			2.5%	2.5%	2.4%	2.4%

VARIABLE CORRELATIONS

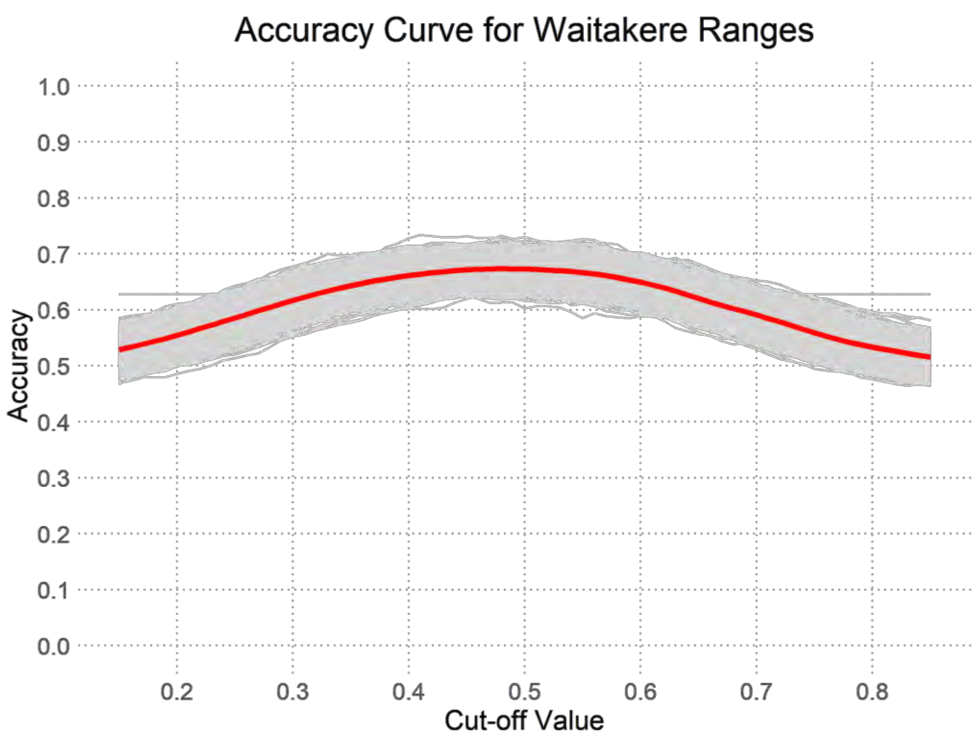
Continuous Variables



Categorical Variables

GeolUnit_vs_Geomorphon	0.036017845
GeolUnit_vs_DistanceToStream	0.007833807
GeolUnit_vs_LCDB	0.088993067
GeolUnit_vs_OLFP	0.007230032
Geomorphon_vs_DistanceToStream	0.281549330
Geomorphon_vs_LCDB	0.163781210
Geomorphon_vs_OLFP	0.302385410
DistanceToStream_vs_LCDB	0.031283368
DistanceToStream_vs_OLFP	0.186404099
LCDB_vs_OLFP	0.032843866

ACCURACY PLOT

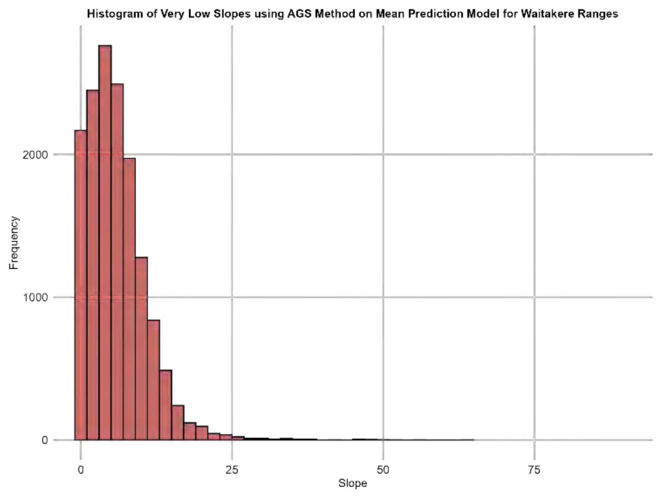


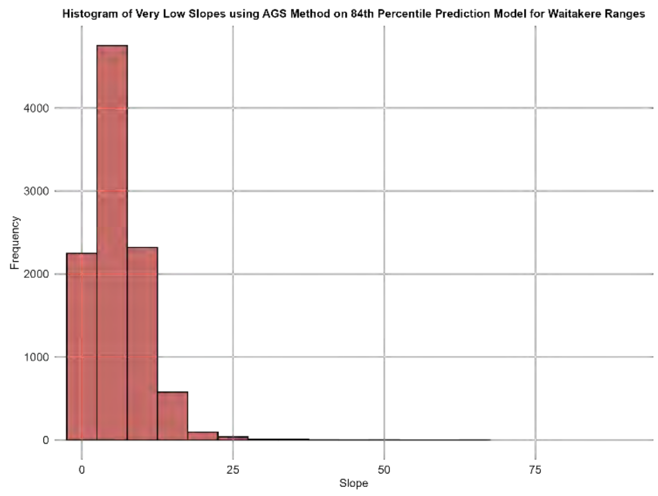
SLOPE ANGLE DISTRIBUTIONS

METHOD 1 (AGS)

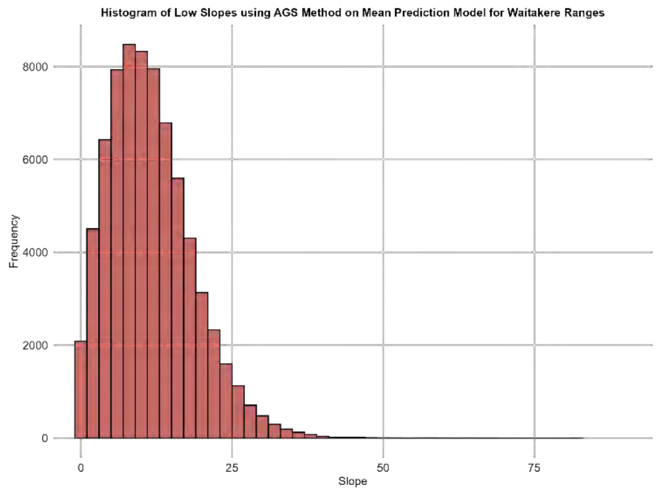
Mean predictions | 84th percentile predictions

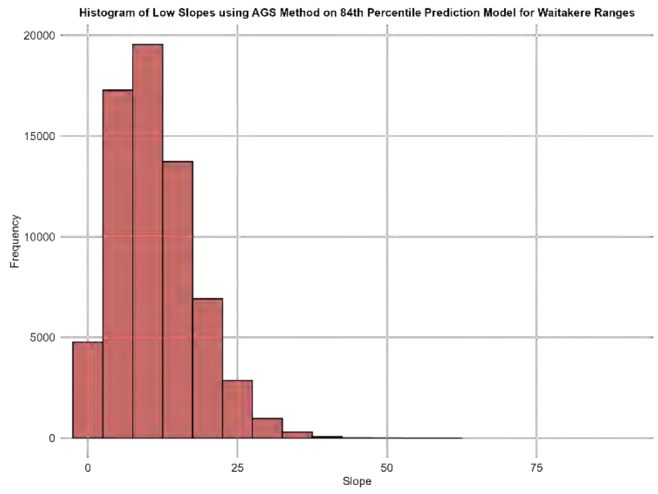
Very Low



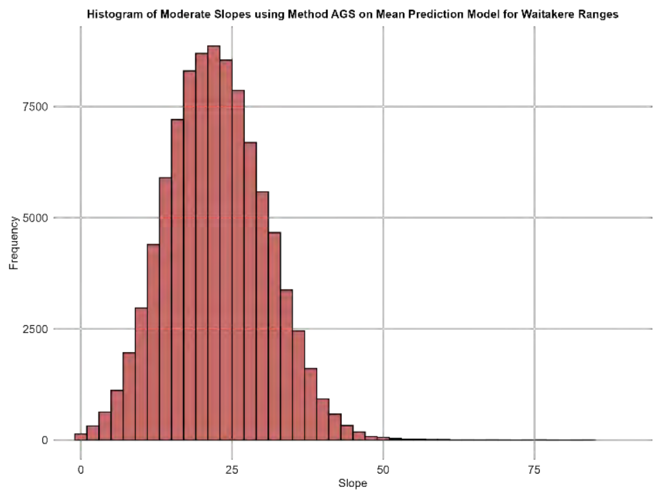


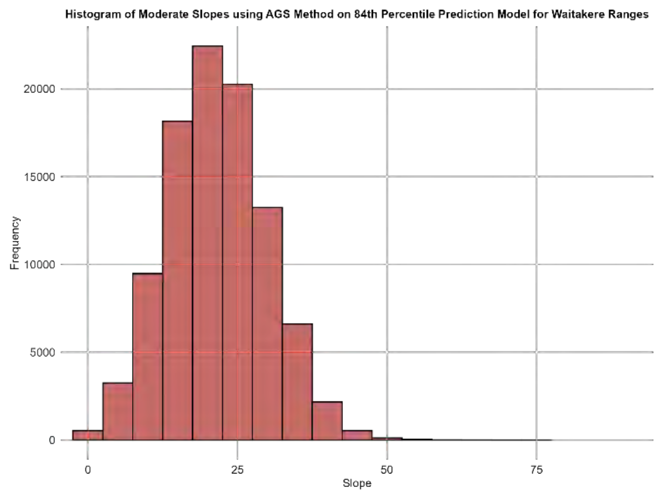
Low



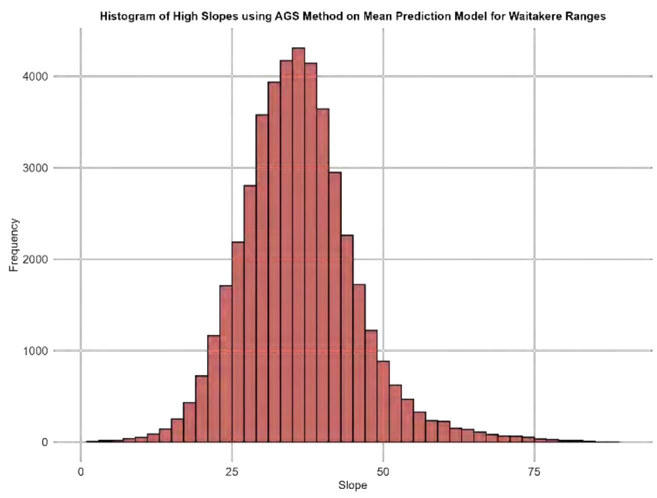


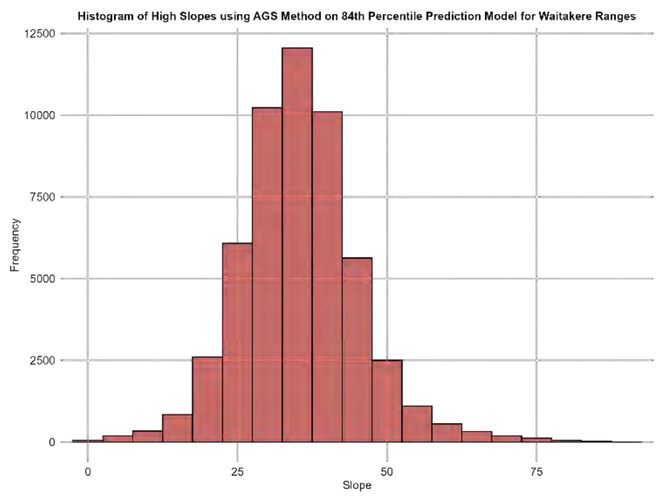
Moderate





High

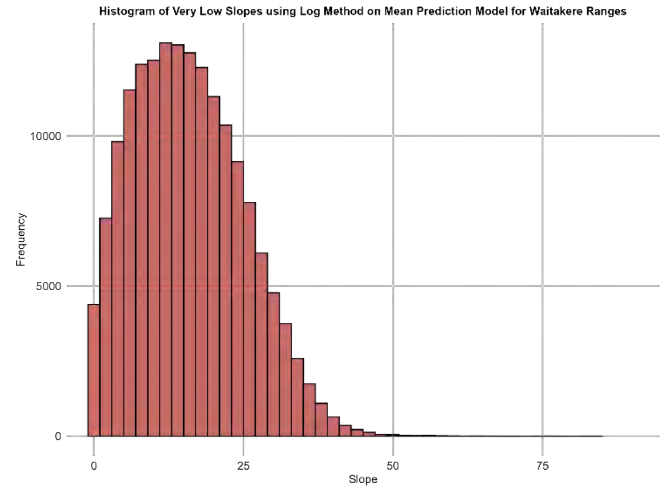


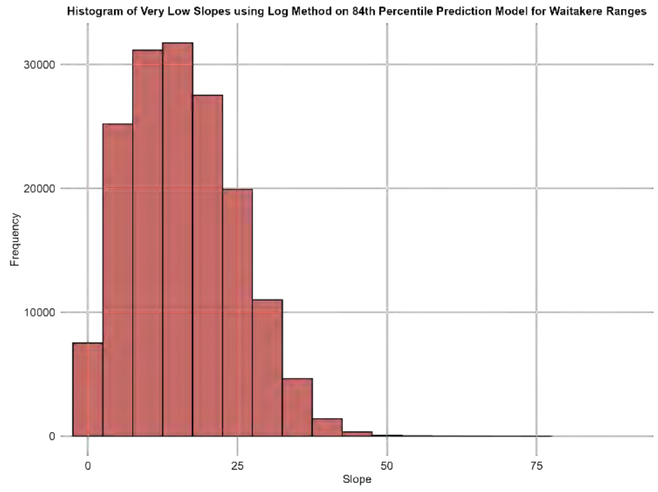


METHOD 2 (LOG BINS)

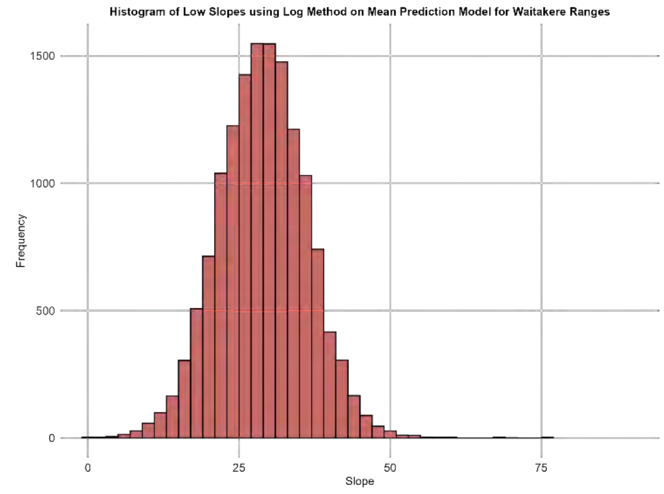
Mean predictions | 84th percentile predictions

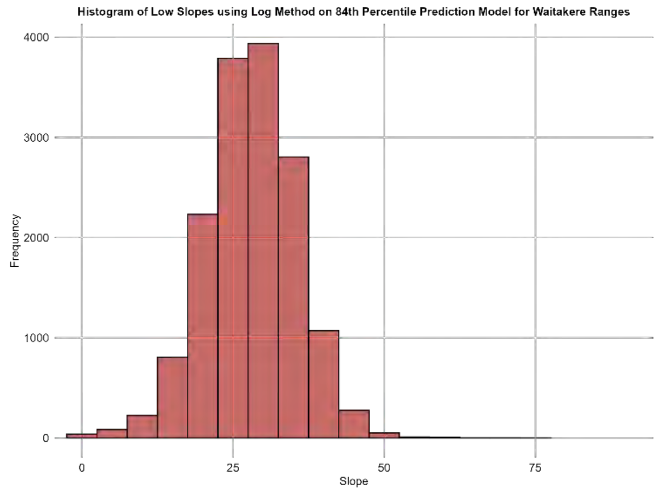
Very Low



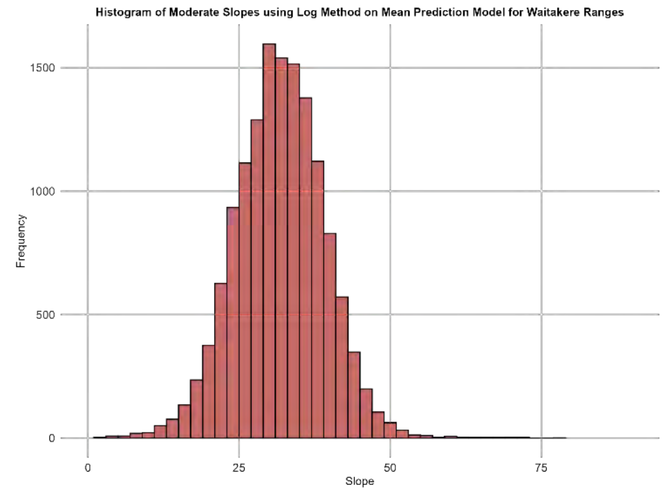


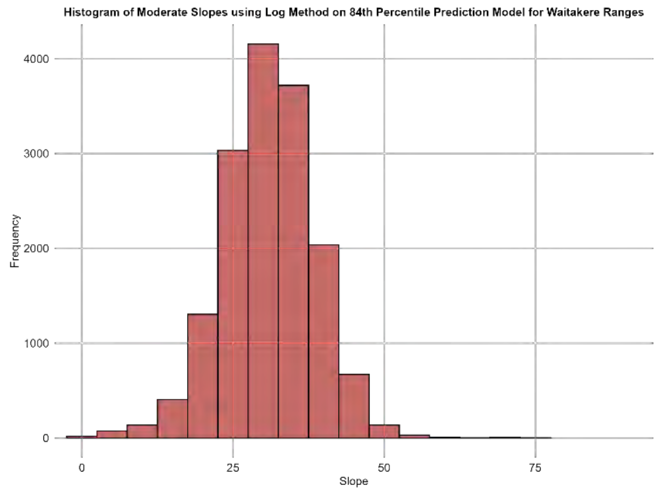
Low



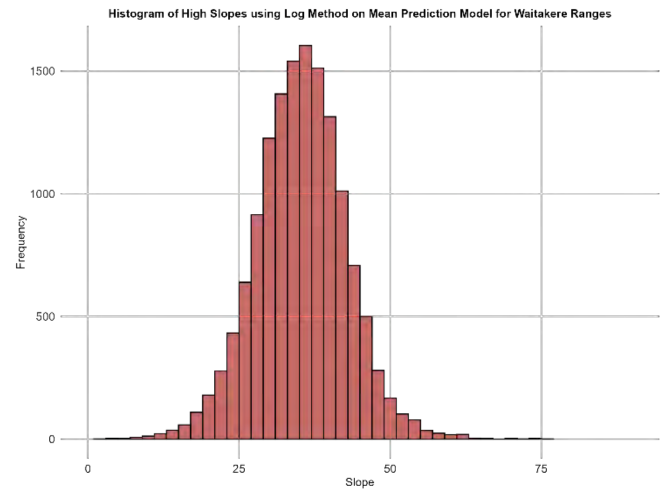


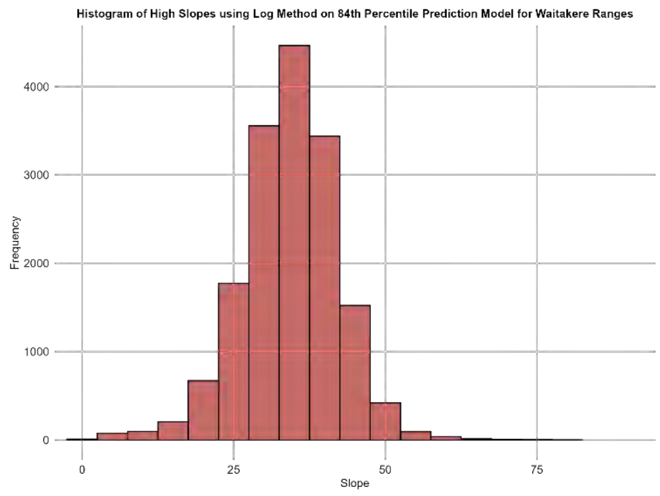
Moderate



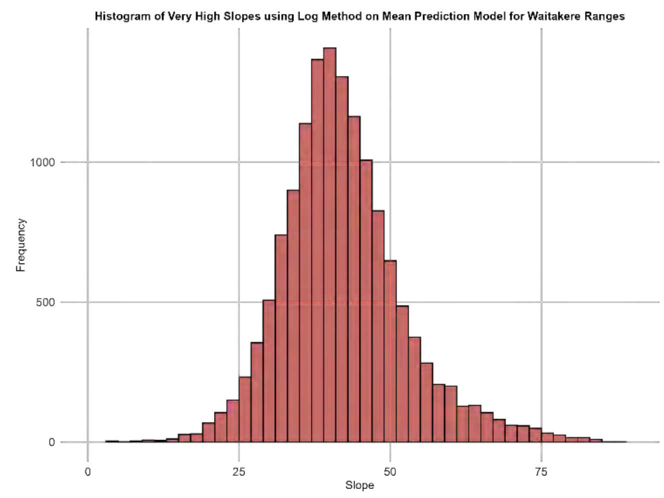


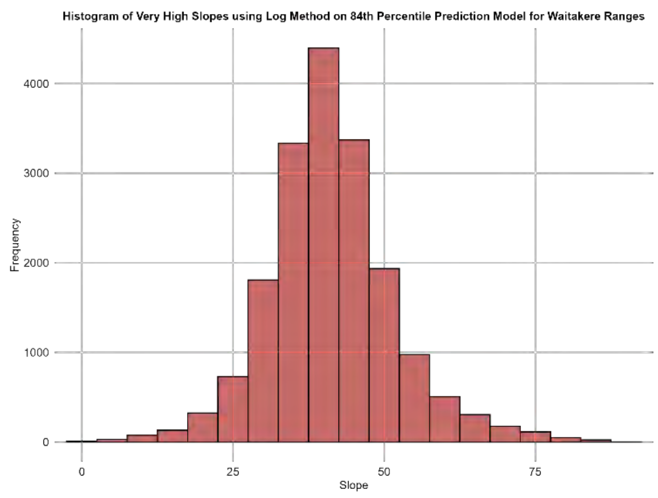
High





Very High

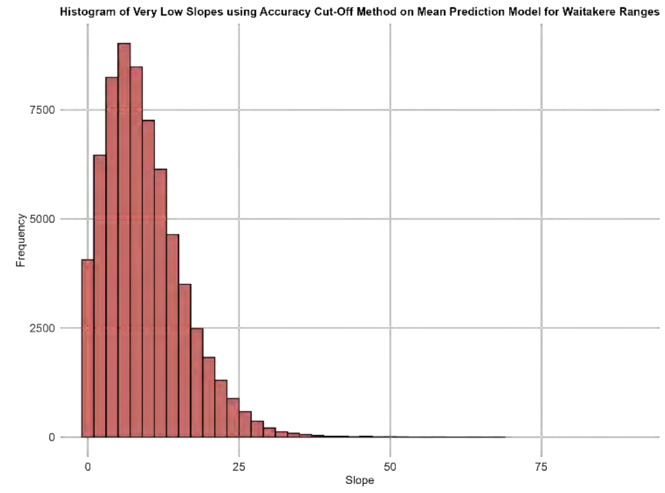


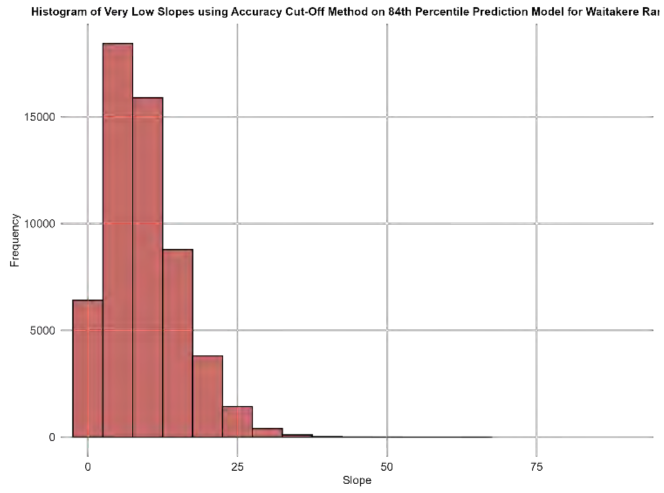


METHOD 3 (ACCURACY CUT-OFF)

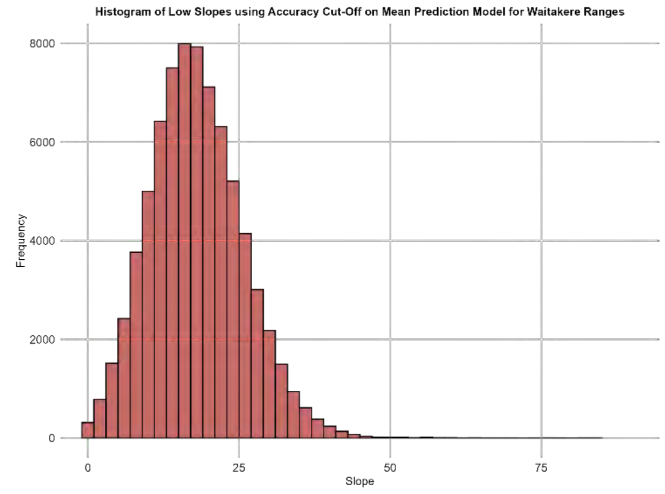
Mean predictions | 84th percentile predictions

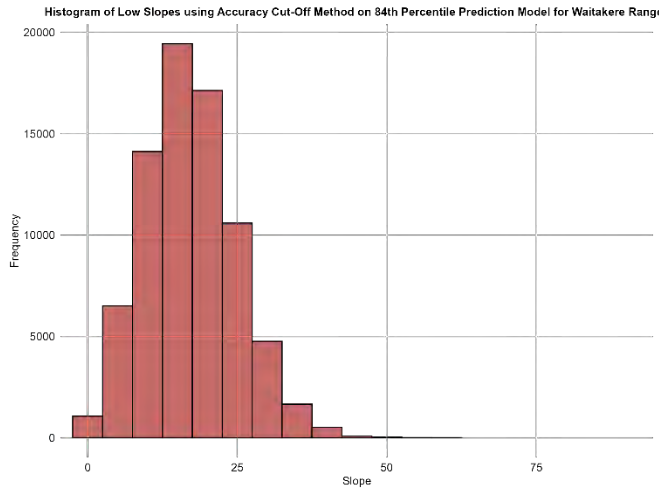
Very Low



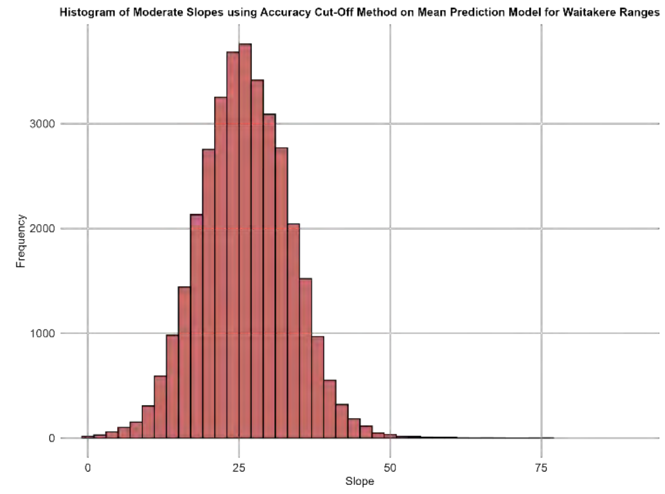


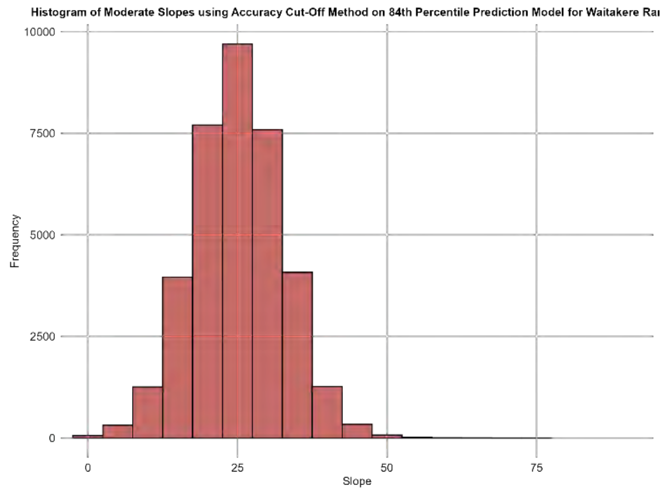
Low



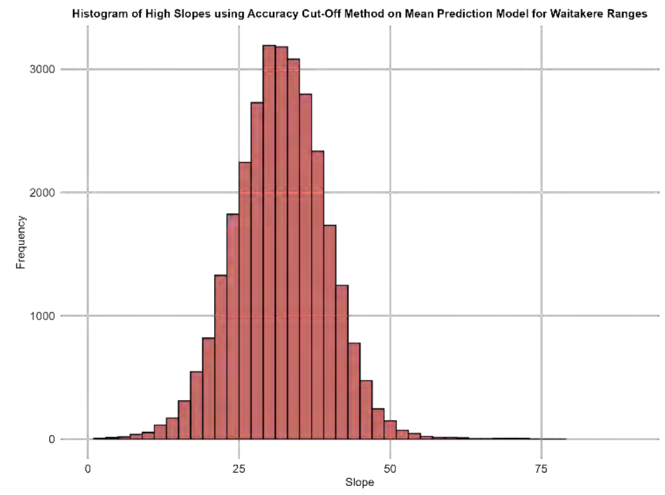


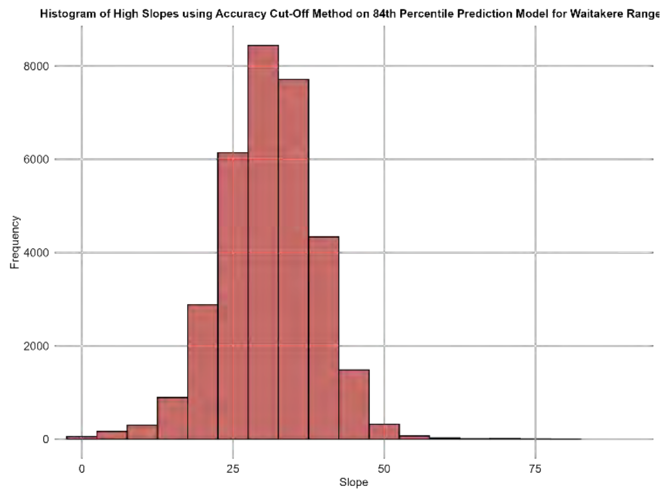
Moderate





High





Very High