Appendix D

RAMMS Debris Flow Analysis

Waitakere Coastal Communities Landslide Risk Assessment

Appendix D – Muriwai RAMMS debris flow analysis report

Auckland Council

15 May 2024

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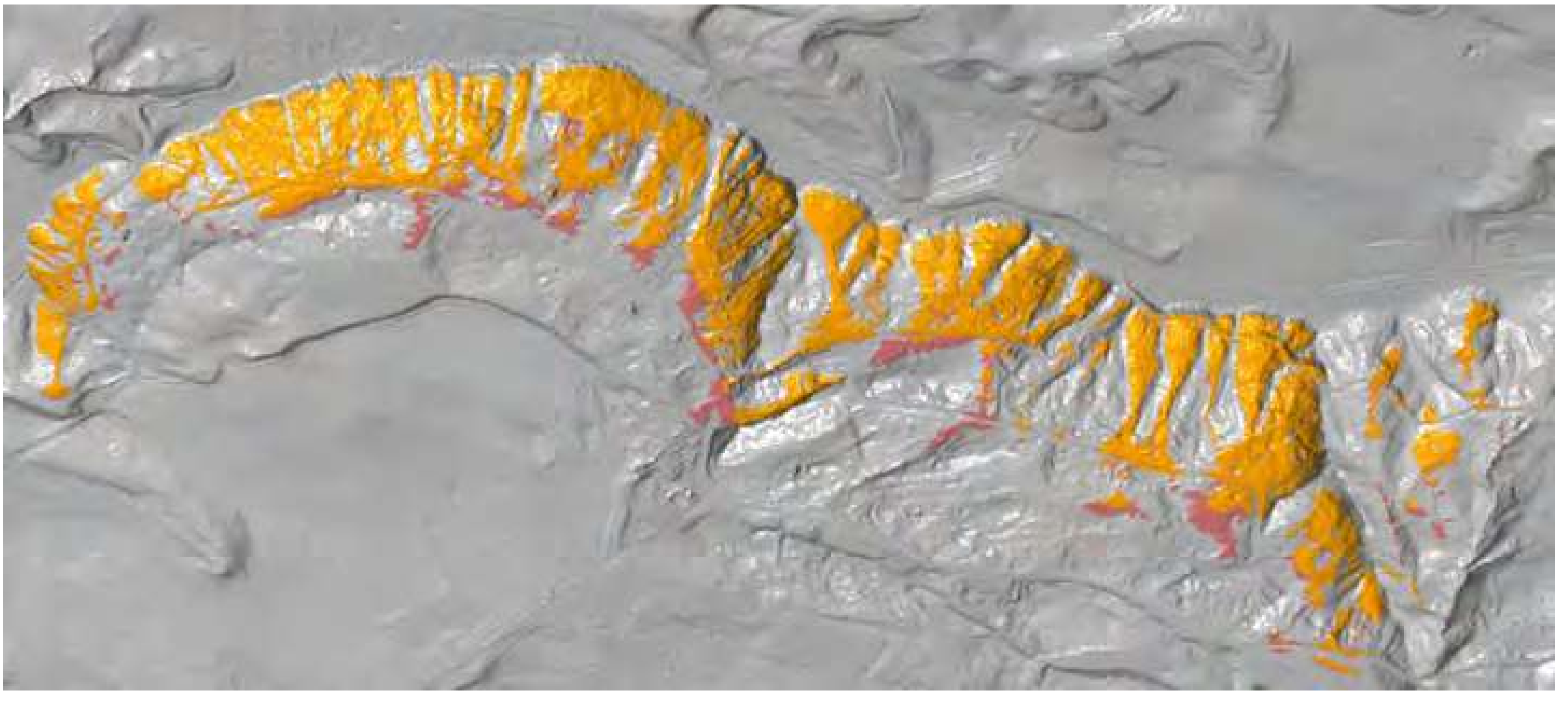

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D1. Introduction

D1.1 Purpose of this report

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

The purpose of this assessment is to present the results of a RAMMS computer-simulated three-dimensional debris flow assessment undertaken to provide guidance on the potential effects of future events on dwellings in Muriwai. In addition, a sensitivity analysis of input parameters is presented. The analysis focus is on the large-scale hazard from the 80 m-high escarpment to the east of Muriwai township that experienced damaging landslides in February 2023. The results from the analysis provide an important part of the GHD loss of life risk study (see Appendix E of the overall report) that will support decision-making by AC on the long-term suitability of sites and dwellings for occupancy.

This report is an appendix to the overall GHD landslide risk report and should be read in conjunction with it, as well as associated appendices. The covering report contains additional background information and the results of other assessments carried out by GHD that are not included herein.

D1.2 Background

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

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

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

The modelling of potential debris flows was identified as an important element of understanding the ongoing future risk to the Muriwai community.

D1.3 Scope

The scope for this work is as follows:

- Establish a ground surface model using data provided by AC.
- Calibrate RAMMS input parameters to replicate the observed runout distance of February 2023 debris flows.
- Identify areas of the escarpment that could be susceptible to future landslides in rare, large rainfall events
- Using RAMMS, simulate the failure of future landslide source areas leading to large-scale, destructive landslides.
- Conduct a RAMMS analysis specifically for Geomorphological Zone 5, which is located at the southern end of Muriwai between Domain Crescent and Waitea Road.
- Provide a plan of the area potentially affected by debris flows of sufficient thickness that could cause loss of life (i.e. greater than 0.5 m).

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

AC requested that this study be limited to the assessment of the effect from 'large scale[2]' landslide hazards originating from the main escarpment located to the south-east of Muriwai because the initial placard assessment was largely aimed at mitigating risks associated with these landslide hazards. Consequently, this report does not consider smaller, more localised landslide hazards that could originate (or may have already initiated) from other areas in Muriwai such as within the footprint of individual residential properties. The exception to this is 3 specific property's (85 and 87 Domain Crescent and 207 Motutara Road). The basis for this is outlined in Section 1.3 (footnote 3) of the Overall Report.

This report has been prepared by GHD for Auckland Council and may only be used and relied on by Auckland Council for the purpose agreed between GHD and Auckland Council as set out in section 1.1 of this report.

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

D1.4 Report structure

The accompanying GHD Engineering Geology report provides a detailed description of the site as well as discussion of site geology and geomorphology, historical landsliding, landslide mapping, landslide classification and slope processes. The reader is advised to consult the accompanying GHD reports for further information not contained herein. A list of report sections is presented in Table D1. A3 plans referred to in this report are listed in Table D2 and RAMMS output figures are presented in Appendix D-1.

Table D1 Summary of accompanying Muriwai landslide risk assessment reports

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

Table D2 List of RAMMS debris flow simulation plans in Appendix A that are associated with this report

A201	Maximum debris height extents for best case, predicted and worst case scenarios -(greater than 0.01 m deep) - overview
A202	Predicted maximum debris height (greater than 0.01 m deep) - overview
A203 – A205	Predicted maximum debris height (greater than 0.01 m deep) - close-up
A206	Maximum debris height extents (greater than 0.5 m deep) - overview
A207 – A209	Maximum debris height extents (greater than 0.5 m deep) - close-up

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

D2. RAMMS Debris Flow Modelling

D2.1 Description of software

The RAMMS Debris flow module (RAMMS) is a three-dimensional numerical software package developed by the WSL Institute for Snow and Avalanche Research and is used to simulate the runout of debris-laden flows in complex terrain. Version 1.8.0 was used for this analysis.

RAMMS is a credible modelling tool that is frequently used in New Zealand and internationally. Like most similar modelling techniques, RAMMS is a simplification of a process that is inherently complex and unpredictable. Consideration of observed landslide behaviour is essential to obtain credible results.

The extent of simulated debris flows can be presented as ‘heat maps’ of depth, maximum depth, maximum velocity or maximum pressure. We have attributed the vulnerability metric of maximum depth in the risk analysis (see Appendix E of the overall report) as being the most relevant to understanding the potential hazard to occupants of dwellings. RAMMS outputs are therefore presented as maximum depth and the modelled landslide runout zones are referred to in this report as the ‘Predicted modelled debris runout zone’.

D2.2 Ground surface model

RAMMS uses a surface ‘digital elevation’ model (DEM) as the base layer for its calculations. It is important to have a representative surface model that accurately depicts slopes, ridges and channels, all of which influence the path of debris flows. Surface models that are insufficiently detailed may give overly conservative results, as the software perceives unrealistically smooth terrain. The RAMMS (2022)[3] guidance document is not definitive on the minimum spacing, but our experience is that a surface model should have points at or closer than 1 m.

We obtained data from AC and publicly available sources. The surface model used included the following:

- LiDAR surface data (1 m point spacing) and aerial imagery (0.15 m resolution) obtained 2016-2018 (provided by AC)
- LiDAR surface data (1 m point spacing) and aerial imagery (0.15 m resolution) obtained 2023 (provided by AC) following Cyclone Gabrielle
- Mapped landslide extents recorded remotely and from GHD 2023 field mapping (see the Engineering Geology Report – Appendix B of the overall report)

Surface data is processed to remove vegetation and dwellings.

Our RAMMS simulation considers whether a pre or post February 2023 DEM is appropriate. The pre 2023 event DEM was used to calibrate existing landslides and the post event DEM was used to model future debris flows as the terrain has been altered by recent debris deposition. Comparison of the elevation of the two DEMs has identified that there is a difference between each model of 0.3 m, which may reflect the accuracy of one or both of the models. This is discussed in more detail in section B3.1.1 of the Engineering Geology Report – Appendix B of the overall report.

D2.3 Input parameter options

Debris flows involve a dynamic interaction of flowing material that is part liquid and part solid. As the mass descends the slope this ratio constantly changes, resulting in complex dynamics within the flow and between the flow and ground. To simulate this, RAMMS uses some input parameters that are described in detail in the supplier user manual (RAMMS, 2022).

The following describes the RAMMS parameters that can be varied:

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[3] RAMMS (2022). RAMMS: DEBRISFLOW User Manual v.8.0. Davos, Switzerland: ETH

Hydrograph and block release

Debris flows are often associated with large, basin-shaped catchments where debris is entrained within floodwaters in a river channel and discharged at the top of a fan ‘apex’. A hydrograph can be used as an input to describe the expected flow over time, which is often developed for a particular catchment. This influences the discharge and duration of debris flow.

Block release is where a thickness of debris for a defined area is released. Block release can be applied to multiple areas per simulation. The initial February 2023 landslides are interpreted as being a solid detachment of weakly cemented sandstone that liquefied during descent. RAMMS does not specifically model this scenario – this is accounted for in the calibration of the input parameters.

Debris flow material properties

- Frictional parameter Mu (µ), which is unitless. It is a measure the basal friction – the friction that occurs during interaction between the surface of the flow and the ground surface below. Landslides with higher Mu values result in shorter and more narrow runouts. RAMMS (2022) suggests a starting Mu value of approximately 0.2, with 0.05 - 0.4 providing realistic results values. Outside this range is not recommended, with Mu of zero giving visco-plastic behaviour and greater than 0.4 seldom producing useful simulation results.
- Frictional parameter Xi (ξ), in units of m/s^2. This represents the viscous-turbulent properties of the landslide slurry. Higher Xi values indicate more laminar flows that travel further. RAMMS (2022) recommends that Xi is between 100 and 200 m/s^2 for granular flow (solid-dominated).
- Flow density (ρ), in units of kg/m^3. Density represents the bulk density of solids and fluids within the flow. RAMMS (2022) recommends a value of 2000 kg/m^3 if details of the landslide are not available.

Stop Criteria

There are two ‘Stop Criteria’ that dictate when a simulation stops running in RAMMS. The simulation will stop at whichever criteria is fulfilled first. The purpose of this is to avoid misleading results due to the expansion of the debris mass at the end of the movement when most energy has been expended. The criteria are:

- The momentum-based ‘Percentage total momentum’ (energy cutoff). The default setting in RAMMS is 5%, i.e., when 95% of the mass has stopped. This can be adjusted to account for faster or slower mass movement speeds. The RAMMS (2022) suggested range for reasonable results is between 1% and 10%. For a value that is too low, the debris flow will continue to creep at extremely low velocity (i.e. the simulation lasts too long) and for a too high value the simulation will terminate prematurely.
- The centre-of-mass based ‘Centre-of-mass velocity threshold’ (m/s). The default setting in RAMMS is 0.2 m/s, i.e., the model terminates when the centre of mass velocity is below this value. This value is useful for address slow, creeping mass movements, but is not appropriate where there is more than one landslide being activated simultaneously. For Muriwai a value of zero is appropriate.
- End Time (s) – This represents the amount of time the simulation will allow the landslide to flow for. It is desirable to have a simulation end due to the Stop Criteria of the landslide or due to low flow rates (‘low flux’). It is less desirable to have a ‘time end condition’, which indicates neither the target stopping criteria nor low flux condition has been met.

Erosion function

The erosion function predicts the depth of erosion of sediment caused by debris flows. This can be used to predict the increase in volume of a debris flow as it travels along a channel. The erosion parameters are: erosion density (of the landslide debris); erosion rate of material from the channel; potential erosion depth; the critical shear stress where erosion can occur, and; the maximum erosion depth. The disadvantage of incorporating erosion is that you cannot specify the release volume before the simulation starts as it is created as a function of the debris flow.

Filtering of depth results

The results of the RAMMS analysis can be filtered to show the depth range of interest. This can be done to remove the presence of thin, non-life-threatening debris at landslide margins.

Effect of vegetation and buildings

The influence of trees acting to impede or add to debris flow damage on February 2023 landslides has been observed. Similarly, buildings may alter the natural path of part or all of a debris flow. It is possible to apply an impassable zone to physically block a simulated debris flow, but predicting the behaviour of individual trees and buildings in an area-wide study is not possible and has not been applied.

D2.4 Model calibration and selected input parameters

2.4.1 Calibration purpose and input parameter selection

Calibration of a RAMMS model with actual debris flow observations is important to account for the unique material and terrain characteristics in a particular location. At the large escarpment south-east of Muriwai there are more than ten large (several tens of metres wide) landslide source areas, all in similar Awhitu Group weakly cemented sandstone (see Appendix B of the overall report for a description of the Engineering Geology). This provides a compelling dataset of landslides and associated debris runout to guide assumptions on future large slope failures on the escarpment. Aligning the RAMMS model with existing failures provides confidence in its application elsewhere on the escarpment.

We calibrated the RAMMS model against the February 2023 landslides shown in Figure D1 and Table D3. In addition, the following values were selected:

- ‘Block release’ of debris
- Stop Criteria:
  - The momentum-based ‘Percentage total momentum’ – 5% was selected. The process for making the selection is presented in Figure D6.
  - The centre-of-mass based ‘Centre-of-mass velocity threshold’ – 0 m/s was selected, which is appropriate for multiple release areas/catchments.
  - End time – this varied between simulations due to the parameters of the RAMMS calculation for the ‘predicted modelled’ scenario. All simulations had an end time of 180 seconds. These met the desirable condition of ‘low flux’.
- Erosion function – this was not used for calibration, as the concentrated channelised flow described in RAMMS (2022) is not observed at Muriwai, with more distributed flows being evident.
- Simulations have been filtered to show maximum depths of greater than 10 mm so that comparisons with actual landslide extents is possible.

The release areas were defined in RAMMS using the mapped source area extents and estimated depth. It was noted that some landslides comprise individual, large source areas, while others have numerous, smaller source areas, with debris combining further downslope. We used both of these configurations for our calibration to represent these cases. The 2016 surface DEM was used to best represent the ground conditions existing at the time of the recent landslides. All RAMMS output figures are presented in Appendix D-1 of this report.

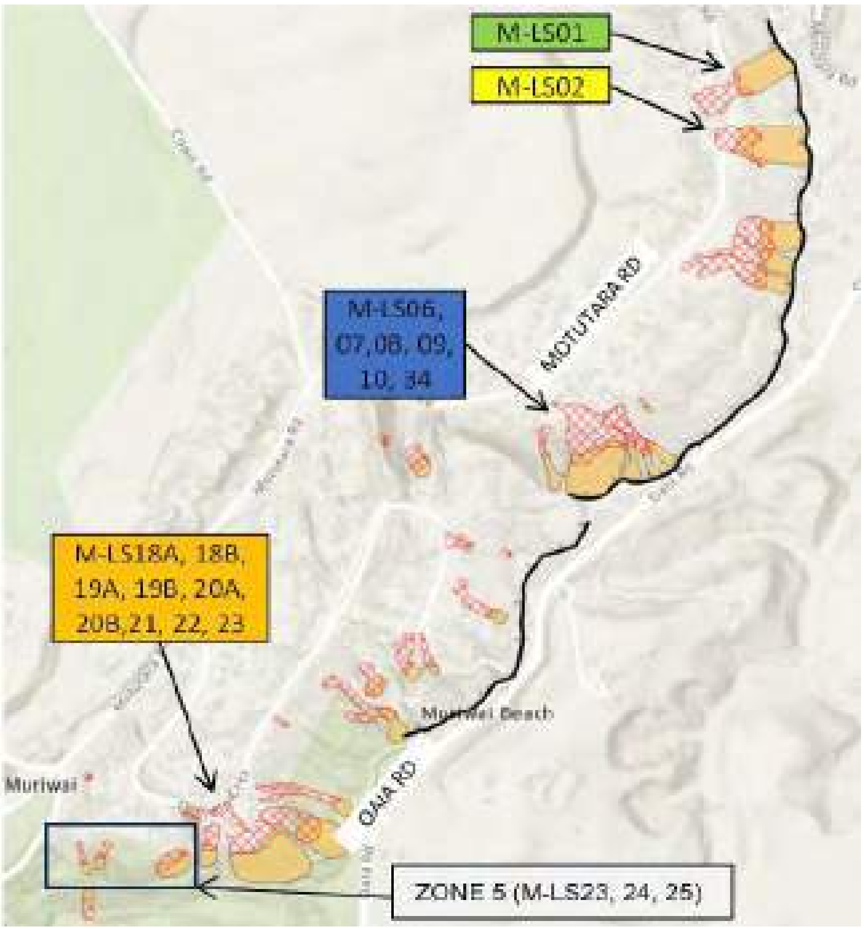

Figure D1 Location of landslides used for RAMMS calibration

Table D3 Landslides used to calibrate the RAMMS simulation. Shading is used to show groupings of landslides. Landslide ID is GHD-named (see Appendix B for full list of landslides).

Landslide ID No.	Release Area (m^2)	Average Release Thickness (m)	Released Volume (m^3)
M-LS01	2400	0.5	1220
M-LS02	1800	0.5	900
M-LS06	400	0.25	101
M-LS07	400	0.25	100
M-LS08	900	0.25	200
M-LS09	1900	0.75	1500
M-LS10	400	0.25	100
M-LS34	600	0.25	100
M-LS18A	200	0.25	50
M-LS18B	200	0.5	100
M-LS19A	800	0.25	200
M-LS19B	2000	0.25	500
M-LS20A	200	0.5	100
M-LS20B	3600	0.75	2700
M-LS21	500	0.25	100

Landslide ID No.	**Release Area (m^2)**	**Average Release Thickness (m)**	**Released Volume (m^3)**
M-LS22	200	0.25	50
M-LS23	700	0.5	400

Where parameters were recommended by RAMMS, these were initially applied and modified to obtain a runout extent that best matched what was observed. This was done by showing the mapped landslide extents beneath a transparent RAMMS overlay. The selected input parameters are presented in Table D4. Calibrated, best-fit output images are presented as Figure D2 to Figure D5.

Table D4 Selected input values for calibration (bold is conservative)

Parameter	Units	Typical Range (bold is conservative)	Range tested	Selected Value For Calibration
Density* (p)	kg/m^3	1800 - **2000**	-	2000
Basal Friction (Mu)	n/a	**0.1** - 0.4	**0.05** - 0.5	0.225
Viscous turbulent (Xi)	m/s^2	100 - **200**	**5 - 200**	87.5

Geomorphological Zone 5

The study area has been divided geomorphologically into six landslide ‘zones’ based on the surface topography, February 2023 landslide characteristics and general geomorphology. The purpose of this is to differentiate areas according to their susceptibility for large-scale landslides. The basis for the zoning and the zone characteristics are described in Section B5.3 of the Engineering Geology Report – Appendix B of the overall report.

There are similarities between Zone 5 and the main escarpment (i.e. Zone 2 to Zone 4), however, the source area is not as high, has different topography and may have groundwater conditions that are more favourable to slope stability. We assess this to mean that the potential extent of future debris flow in Zone 5 is better evaluated by having a specific RAMMS calibration for simulation purposes[4]. The landslides calibrated in Zone 5 were M-LS23, M-LS24 and M-LS25 (see Table D5). The release thickness for each landslide was adjusted with the RAMMS input values in Table D6 to best match observed landslide debris runout.

Table D5 Landslides used to calibrate the RAMMS simulation. Shading is used to show groupings of landslides. Landslide ID is GHD-named (see Appendix B for full list of landslides).

Landslide ID No.	**Release Area (m^2)**	**Average Release Thickness (m)**	**Released Volume (m^3)**
M-LS23	700	0.3	210
M-LS24	130	0.2	26
M-LS25	130	0.1	13

Table D6 Selected input values for calibration

Parameter	Units	Selected Value For Calibration
Density* (p)	kg/m^3	2000
Basal Friction (Mu)	n/a	0.4
Viscous turbulent (Xi)	m/s^2	500

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[4] The Zone 5-specific information contained in this report have been previously documented in a letter to AC on 6 December, titled Muriwai Zone 5 reassessment of landslide risk following updated RAMMS debris flow modelling

2.4.2 Calibration observations

In general, the RAMMS modelling was able to be broadly matched to the total travel distance of the February 2023 landslides observed in the field. The following were observed during the calibration process:

- Simulated small debris flows travelled significantly further than in reality (see Figure D2 for an example of this). This is likely due to the resistance generated by large trees and dense vegetation. In addition, other factors may mean there is an insufficient supply of liquefied debris. Small debris flows would require a specific calibration to provide a credible model.
- The debris flow terminal lobe modelled as being wider in the northern part of Motutara Road (see Figure D3). This could be due to the influence of large trees or buildings, several of which were destroyed in the event.
- Relatively thin layers (less than 200 mm) of debris modelled as affecting areas that were not damaged by debris flows (see Figure D4).
- Stop criteria – the default values provided in RAMMS are adequate, as confirmed by our stop criteria analysis (see Figure D6).

D2.5 Sensitivity analysis

A sensitivity analysis tests the influence of individual model parameters to help understand the relative importance of the elements upon which the model is based. It provides focus for the critical input parameters. The process involves performing repeated RAMMS simulations with a change in one parameter, usually to an extreme high and/or low value. The parameters that were tested are discussed below.

Basal friction parameter Mu

This was tested in approximately 20 simulations using a range of Mu = 0.05 to 0.5. The RAMMS simulation was very sensitive to Mu, with runout varying by more than 50 m downslope (see Figure D10).

Viscous-turbulent frictional parameter Xi

This was tested in approximately 16 simulations using a range of Xi = 5 to 200 m/s^2. The results are nearly identical showing the simulation is not sensitive to Xi (see Figure D11). A comparison of the debris flow extent of Xi = 87.5 m/s^2 (the GHD-selected value) and 150 m/s^2 (RAMMS, 2022 mid-range value) also showed minimal difference in debris flow extent – mostly less than 1 m horizontally (see Figure D12). Broader, less channelised flows travel slightly further with Xi =150 m/s^2.

Erosion function

Although the erosion function was not considered appropriate for use at Muriwai, the sensitivity of its use was tested by comparing the simulated distribution of debris with the function turned on and off. This confirmed that the simulation is not sensitive to the erosion function (see Figure D13).

Multiple block release

Our simulation does not predict which landslide sources will become debris flows in a particular event, instead presenting the debris flow potential for all sources at one time. We have tested to see if there is an effect of multiple adjacent simulated landslides coalescing and travelling further than would be the case of an individual landslide. To do this, the debris flow runout for three landslide sources was simulated individually, then all three sources were simulated simultaneously (see Figure D14).

This showed that modelling coalescing of failures from numerous landslides increases the debris flow runout distance only slightly at Muriwai – typically less than 1 m horizontally, but up to 4 m in some areas.

D2.6 Inferred future landslide source areas

Potential landslide failure zones have been identified based on having similar geomorphology (ground shape) and geology to February 2023 landslide source areas. For example, the bowl-shaped head-scarp shape of recent landslides observed at the crest of the escarpment is similar to the shape of the escarpment where failures did not occur in 2023 (see Figure D9 in Appendix D-1) but have almost certainly occurred at some time in the past. The susceptibility of landslides across the study area has been inferred as variable, however, as a function of the local topographical landform. This is defined as 'geomorphological landslide zones' and outlined in further detail in Section B6.3.. We have assumed that future landslides on the escarpment have the potential to fail with similar damaging effects as the February 2023 landslides. Inferred future landslides were used as RAMMS debris flow source areas.

D3. Final model and analysis results

D3.1 Final simulation input parameters

The key parameters of Mu and Xi used for the prediction of future failure runout distances (the 'predicted' scenario) are those calibrated from the extent of February 2023 debris flow runouts. In addition, we tested the runout using conservative and non-conservative values (see Table D7).

The post-February 2023 DEM was used to model future potential debris flow. The release area applied to all landslide source areas (i.e., existing landslide areas and potential future landslide areas).

Table D7 ***Frictional parameters for the predicted debris flow runout. Conservative (worse case) and optimistic values are presented for comparison.***

RAMMS input type	Input parameter Mu	Input parameter Xi (m/s^2)	Colour in Fig A201	Colour in A203-A206
Predicted	0.225	87.5	🟥	🟥
Non-conservative (optimistic)	0.3	75	🟩	Not shown
Conservative (worst case)	0.15	200	🟨	- - - - - - - -

Geomorphological Zone 5

The parameters used in Zone 5 are presented in Table D8.

Table D8 ***Frictional parameters for the predicted debris flow runout. Conservative (worse case) and optimistic values are presented for comparison.***

RAMMS input type	Input parameter Mu	Input parameter Xi (m/s^2)	Colour in Fig A201	Colour in A203-A206
Predicted	0.4	500	🟥	🟥
Non-conservative (optimistic)	0.4	500	🟩	Not shown
Conservative (worst case)	0.4	100	🟨	- - - - - - - -

D3.2 RAMMS debris flow results

The outputs from the RAMMS debris flow analysis have been filtered and variously presented to illustrate a scientific and defensible modelling approach. Care should be taken to use the information in the intended context.

The presented A3 results figures associated with this report (listed in Table D2 and presented in Appendix A) in the escarpment area are as follows:

- **A201** – which shows the modelled debris extents for the non-conservative (optimistic) case, predicted and conservative (worst) case scenarios. It is filtered to show all depth above 0.01 m (1 cm). Importantly, it shows the ‘F-angle’ estimated runout zone used by AC to inform property the initial placard assignment. **This should be viewed only for general information and understanding RAMMS.**
- **A202-A205** – shows the modelled debris extents and maximum depth for the predicted scenario. It is filtered to show all depth above 0.01 m (1 cm). **This should be viewed only for general information and understanding RAMMS.**
- **A206-A209** – show the predicted modelled runout for debris flows that are greater than 0.5 m (50 cm) deep. Debris flows of or greater than this depth are considered to have the potential to severely damage or destroy a dwelling, if impacted (detailed in Section E4.6 of Risk Assessment Report in Appendix E). **These should be viewed to understand the potential modelled effects of debris flows on individual dwellings.**

The above results include the Zone 5-specific modelling.

D3.3 Data presentation in plans

We have made the following modifications to the raw RAMMS output to clarify the information in Figures A206-A209:

- Smoothing of lines – the output is a blocky line that has been manually smoothed (see Figure D15).
- Removing debris flow shading from the landslide source area – the RAMMS output shows red shaded debris in the source area. This has been removed so this area is not obscured. Occasionally it is left in where a dwelling is nearby to demonstrate the hazard (see Figure D16).
- In some areas there are small zones a few metres wide that have less than 0.5 m debris thickness modelled. For simplicity, these have not been shown as the hazard to dwellings is not changed by them (see Figure D17).
- Isolated zones of predicted debris flow – there are some instances of isolated zones, or islands, of modelled debris. These do not intuitively look correct, however, they can be explained as being due to the flow passing over uneven terrain and being below the 0.5 m filter when going over a crest (e.g. as for a waterfall) and accumulating in a low point (see Figure D18).

D3.4 Simulated escarpment debris flow results compared to property placard status

The following observations can be made about the extent of predicted escarpment RAMMS debris flow results (greater than 0.5 m thick, i.e. potentially causing fatalities) in relation to red placarded properties:

- The modelled debris flow reaches approximately two-thirds of red placarded properties.
- Most of these properties are close to the escarpment (i.e., the landslide source)
- Localised topographic variations have directed simulated debris flows towards some houses and away from others.

Yellow placarded properties are mostly outside of the predicted simulated debris flow of greater than 0.5 m.

D3.5 Quantification of overlap of actual compared with modelled debris flow runout area

To measure the agreement of our RAMMS calibration with debris flow runout extents, we support our qualitative, visual comparison of modelled results with a quantitative assessment using the methodology set out in Heiser et al. (2017)[5]. This quantifies the amount of overlap between landslide debris runout and that modelled in RAMMS. The parameters used and calculations are presented in Table D9. A visual representation of the assessment is presented in Figure D19.

Table D9 ***Summary of calculations for overlap of actual compared with RAMMS modelled debris flow runout area***

Parameter	Formulae	Comments
Ω: Fitting parameter	$\Omega = \alpha - \beta - \gamma$	Possible range of 1 (perfect fit) to -1 (no overlap)
α: Overlap ratio	$\alpha = \frac{X}{T}$	Is the ratio of overlap runout area (X) to the total combined footprint of the simulated and observed runout area (T)
β: Underestimation ratio	$\beta = \frac{U}{T}$	Is the ratio of underestimation of debris in the model (underestimated modelled runout area (U) / the total combined footprint of the simulated and observed runout area (T))
γ: Overestimation ratio	$\gamma = \frac{O}{T}$	Is the ratio of overestimation of debris in the model (overestimated modelled runout area (O) / the total combined footprint of the simulated and observed runout area (T))

Graphs showing the relative amounts of the overlap parameters are presented in Figure D20 and Figure D21 in Appendix D-1. This analysis indicates the following:

- More than half of the RAMMS simulated debris flow area overlap with the observed runout area for each landslide sources considered in the calibration process (i.e. α is greater than 50%)
- There is minimal underestimation of the runout by the RAMMS simulation (i.e. β is less than 0.1)
- There is some overestimation of the runout by the RAMMS simulation (i.e. γ is between 0.2 and 0.5)

The resultant fitting parameter (Ω) values are all greater than zero, indicating a reasonable fit that is not overly dominated by underestimation or overestimation. We interpret this to mean that that the calibration has a reasonable balance of fit.

Table D10 ***Values calculated for fitting parameter Ω***

Landslide Area ID	Ω
M-LS01	0.2
M-LS02	0.3
M-LS03- M-LS04	0.4
M-LS06-LS10, M-LS34	0.5
M-LS18- M-LS22	0.2
M-LS23	0.1

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[5] Heiser M., Scheidl C. and Kaitna R. (2017). Evaluation concepts to compare observed and simulated deposition areas of mass movements. Comput Geosci, 21:335-343

D4. Conclusions

- A robust RAMMS debris flow analysis has been conducted using simulated landslide sources areas similar to the damaging February 2023 Cyclone Gabrielle, and from potential, future sources.
- Geomorphological Zone 5 landslides have been used to calibrate specific parameters for RAMMS analysis due to the relatively short debris flow runout distance when compared to other zones.
- A quantitative comparison of the actual landslide runout areas with that determined from RAMMS simulation indicates a reasonable fit.
- The predicted outcome of the simulation is that over 40 currently red-placarded dwellings could be subjected to impact by escarpment landslide debris that is greater than 0.5 m thick as shown on Figures A206 and A209. This has been assessed by GHD’s risk assessment in Appendix E as having the potential to cause fatalities, especially if large trees are mobilised by the landslide.
- Yellow placarded properties are largely beyond the extent of the escarpment landslide debris that is greater than 0.5 m thick.
- The RAMMS predicted runout extent of damaging debris (i.e. more than 0.5 m maximum thickness) is in broad agreement with the ‘F-angle’ empirical landslide hazard prediction work undertaken by AC to allocate the original emergency property placards.

D5. Limitations

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

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

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

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

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

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

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

Appendices

Appendix D-1

Figures

The following is a presentation of RAMMS debris flow analyses outputs. All figures have North to the top of the page.

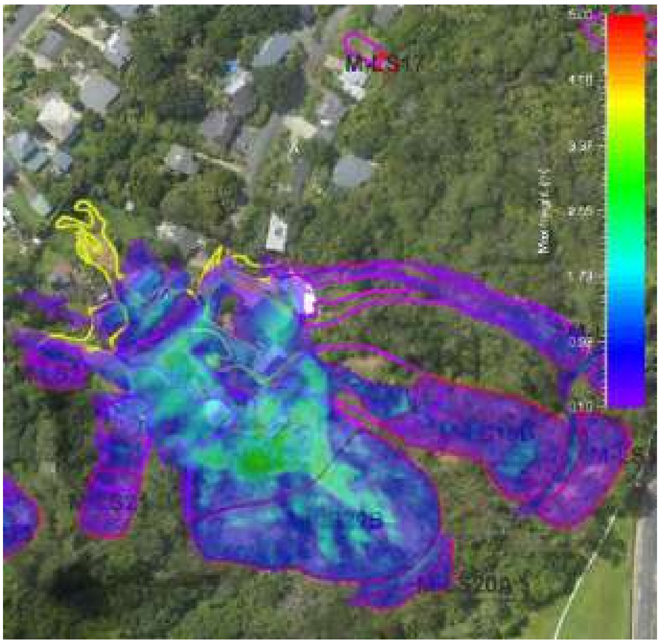


Figure D2 ***Best calibration of large slides southeast of Domain Crescent (M-LS18A, 18B, 19A, 19B, 20A, 20B, 21, 22 & 23). Mu = 0.225, Xi = 87.5, showing with 0.01-5 m filter. Note small landslide on the left that modelled as travelling further than observed.***

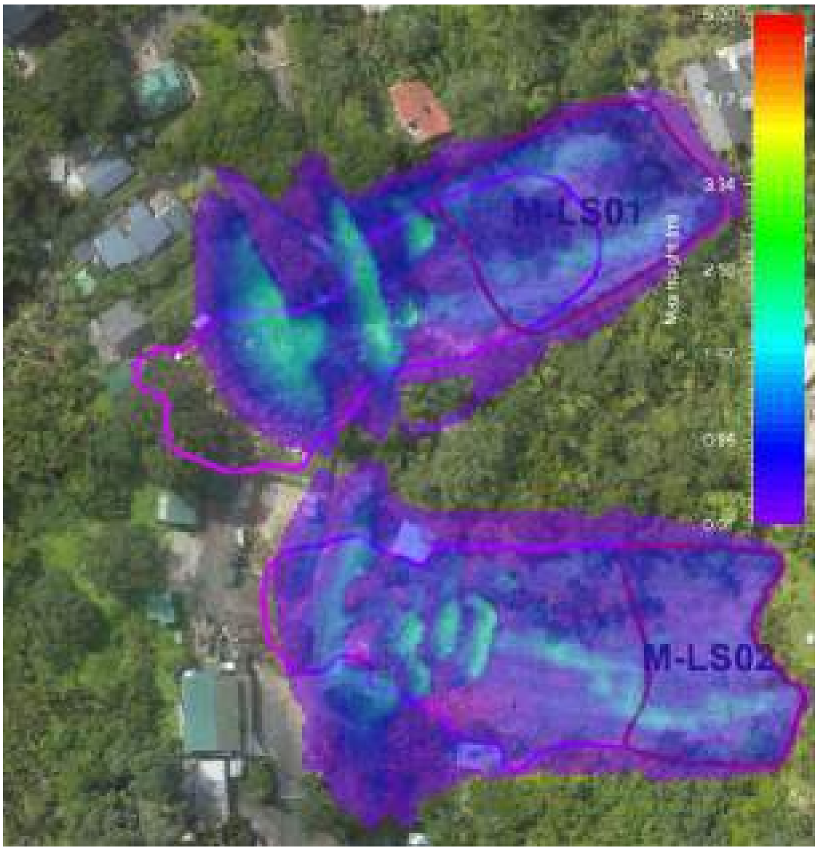


Figure D3 ***Best calibration of large slides at north end of Motutara Road (ID M-LS01 and M-LS02). Mu = 0.225, Xi = 87.5, showing with 0.01-5 m filter. Note modelled debris flow lobe is wider than observed.***

Figure D4 ***Best calibration of large slides at Motutara Road (M-LS03, M-LS04A and M-LS04B). Mu = 0.225, Xi = 87.5, showing with 0.01-5 m filter***

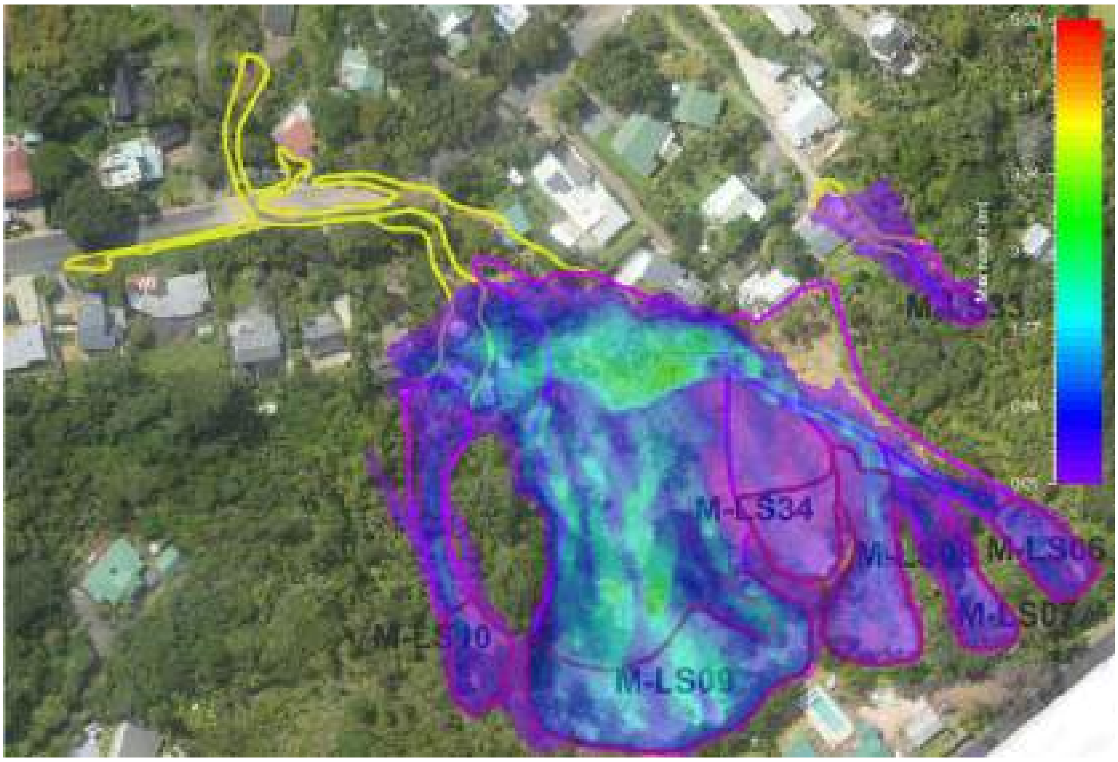
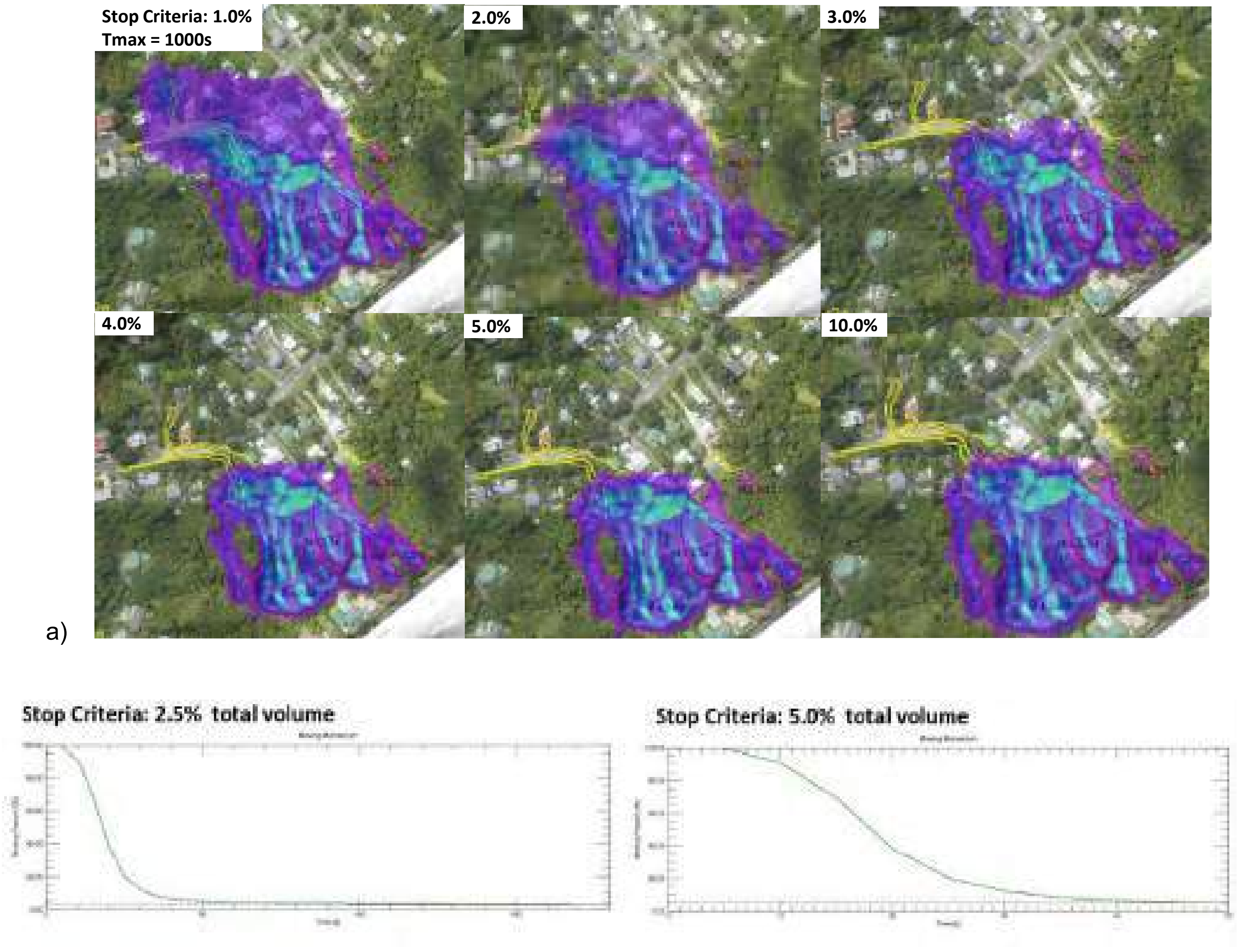


Figure D5 ***Best calibration of large slide at Motutara Road (M-LS06, 07, 08, 09, 10, 33 & 34). Mu = 0.225, Xi = 87.5, showing with 0.01-5 m filter***



b)

Figure D6 *The selection of the RAMMS momentum-based ‘Percentage total momentum’ stop criteria (for Xi = 150 m/s^2 and Mu = 0.2).*
a) The percentage value of less than 5% shows a wide, creeping debris flow at the end of the simulation (showing 0-5 m maximum debris thickness). For scenarios above 5% the simulated debris extents is similar.
b) The relationship between Moving Percent with time. This shows that a lower percentage total volume Stop Criteria (left), indicated by the red line, leads to longer runout times than when a higher percentage total volume is selected (right). If the lower percentage is used, the result is a debris flow extent that slowly expands towards the end of the simulation.

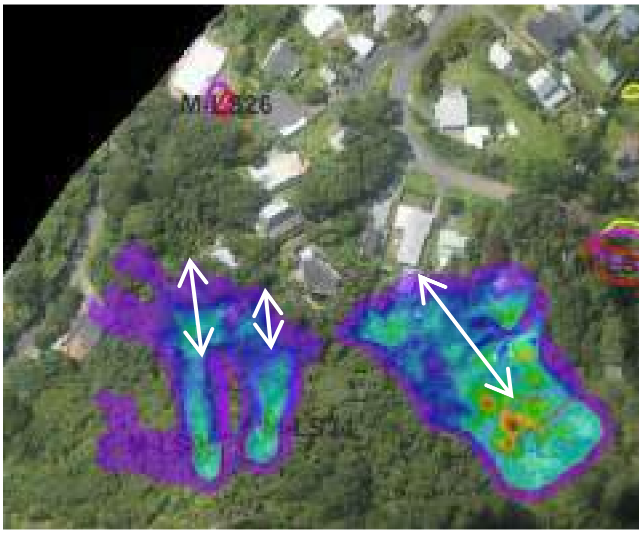


Figure D7 Zone 5 RAMMS simulation showing how the use of (Revision 0) analysis parameters are overly conservative. White arrows show the debris travelling beyond the mapped landslide extents.

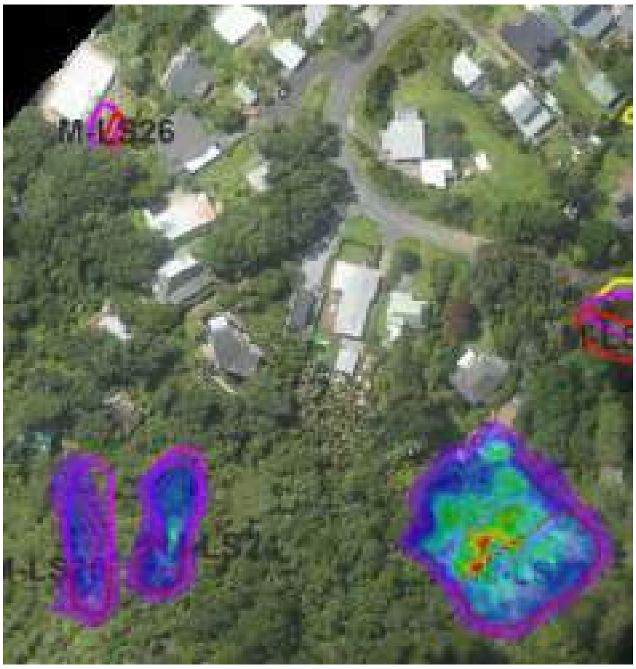


Figure D8 Zone 5 RAMMS calibration using parameters that gives the best match to observed landslide runout

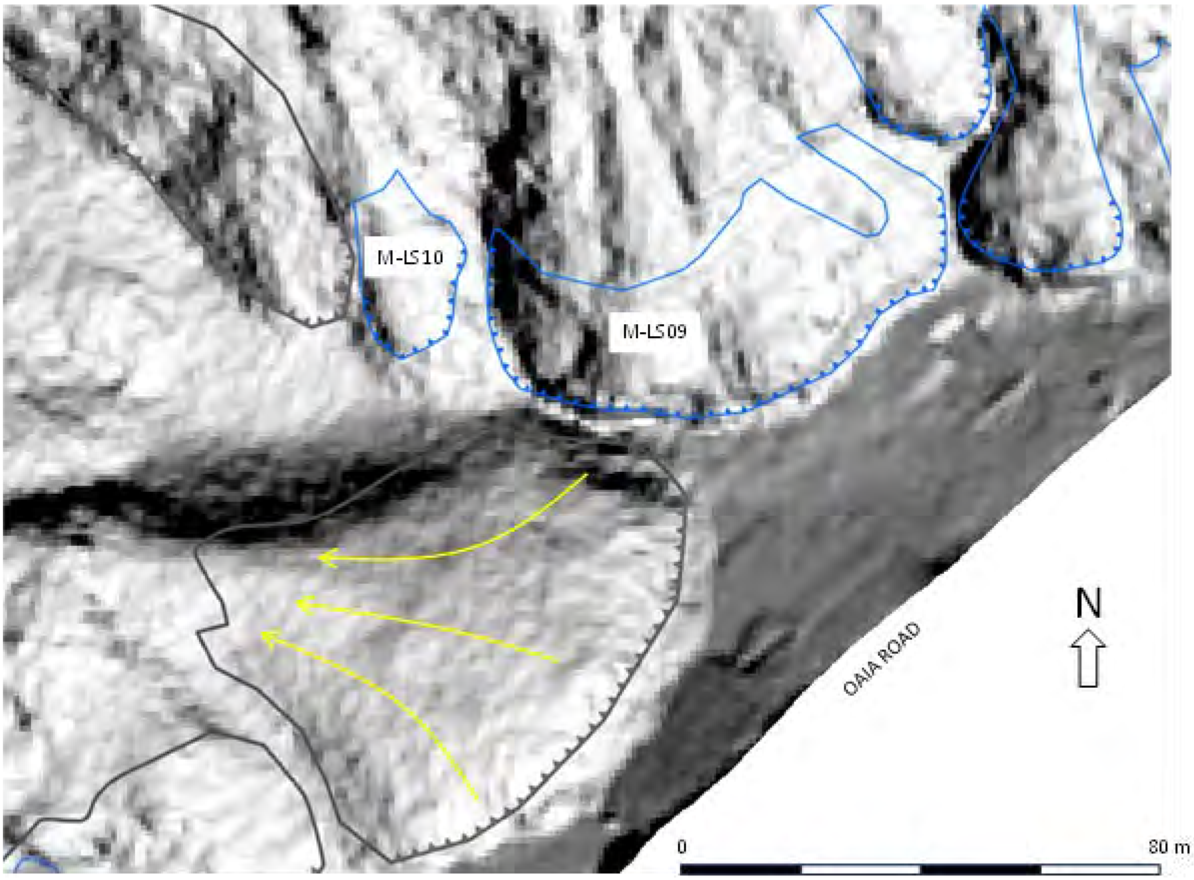


Figure D9 ***Potential landslide failure zones have been defined by GHD based on having similar geomorphology (ground shape) and geology to February 2023 landslide source areas. The above example shows a potential landslide source zone (grey outline) that has similar bowl-shaped characteristics to recently failed blue areas. Background surface model has a 'hill shade' applied to highlight the geomorphology. Location is below the escarpment and west of Oaia Road (see Figure A115 in Appendix A).***

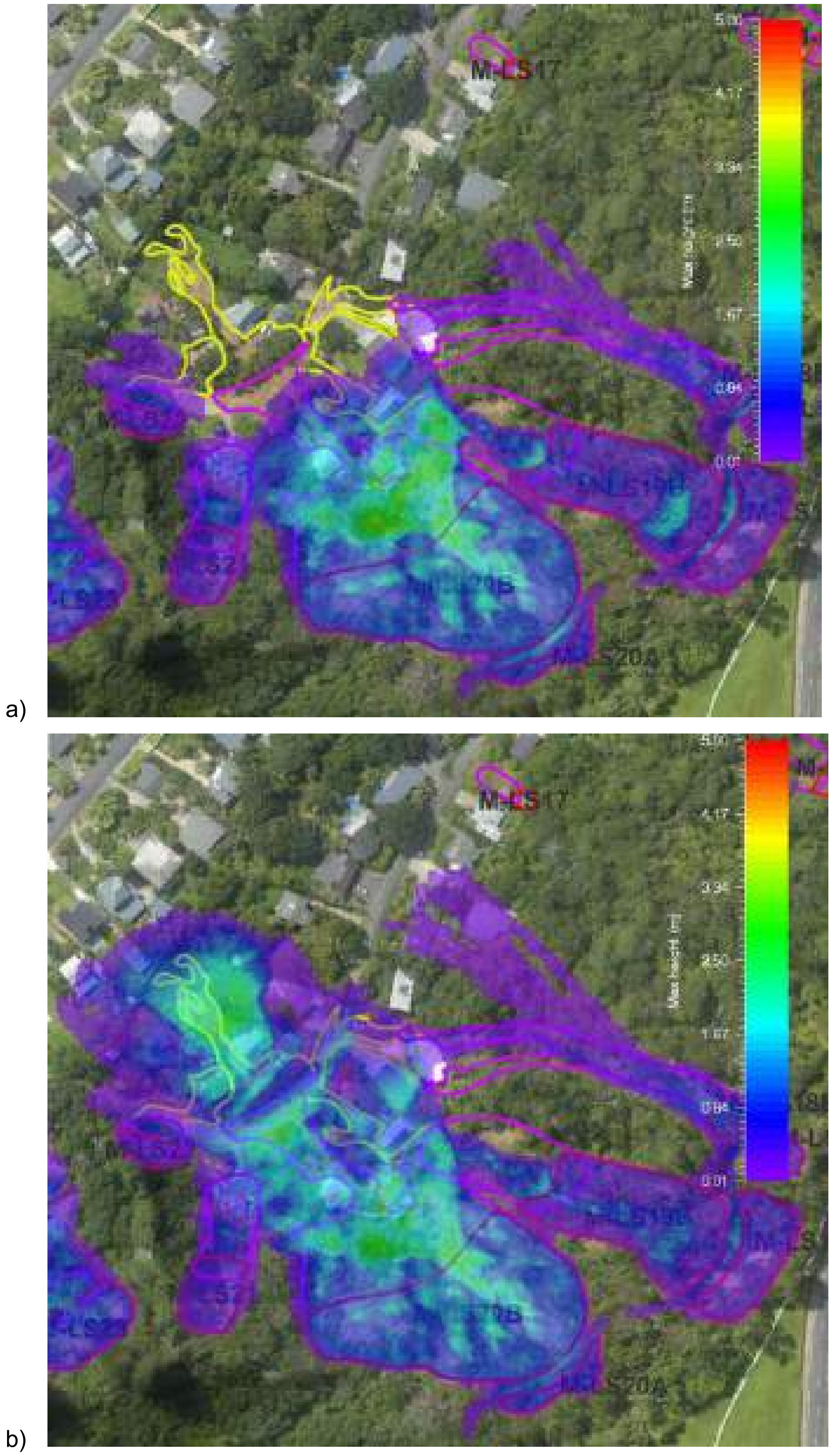


Figure D10 *Comparison of RAMMS input parameter Mu (basal friction), with a) Mu = 0.3 and b) Mu = 0.15. All other parameters are unchanged. Note that simulated debris travelled much further with the lower Mu value.*

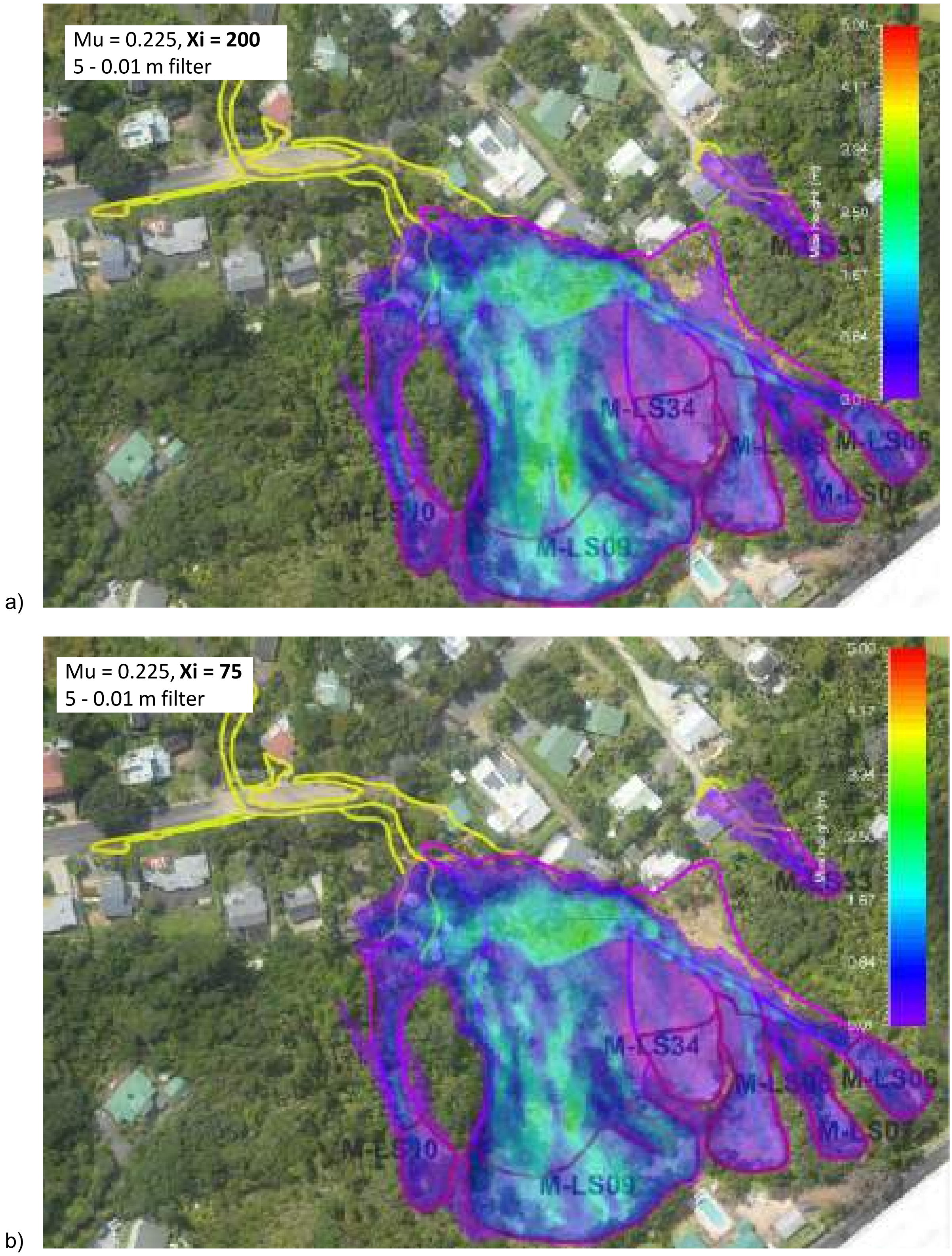


Figure D11 *Comparison of RAMMS input parameter Xi (viscous-turbulent friction), with a) Xi = 200 and b) Xi=75. All other parameters are unchanged. Note that the results are nearly identical, and the simulation is not sensitive to Xi.*

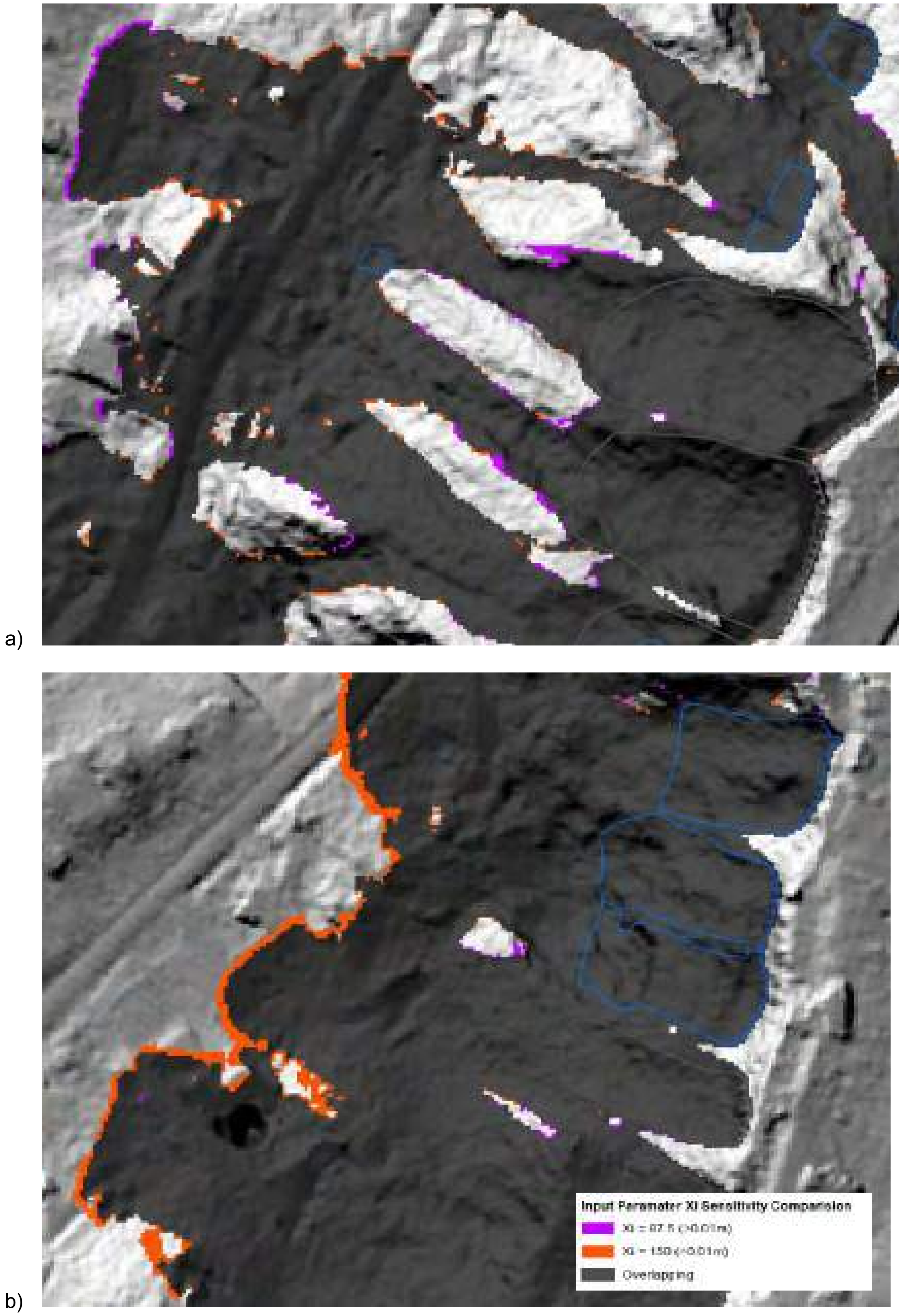
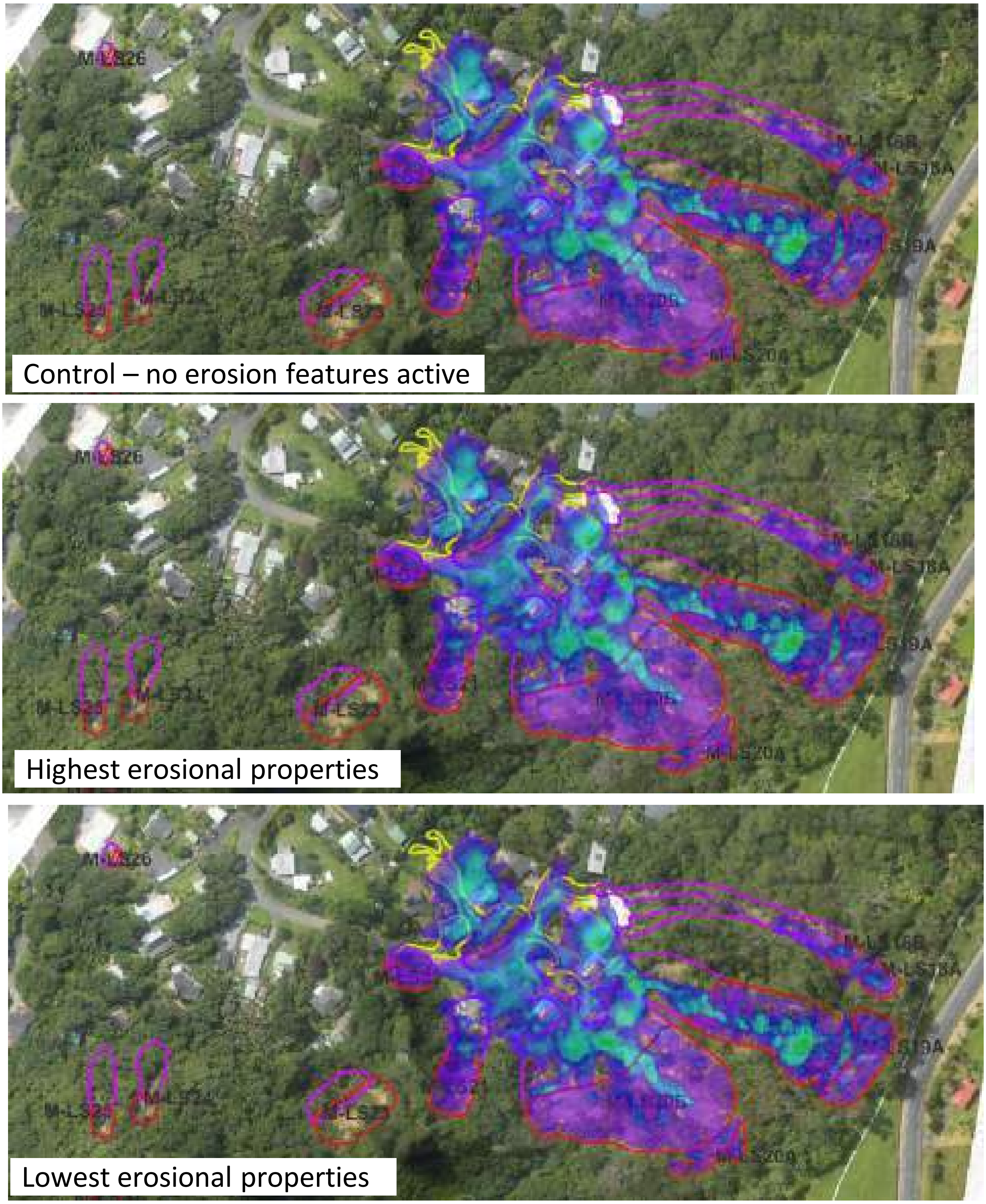


Figure D12 ***Comparison of RAMMS input parameter Xi (viscous-turbulent friction), with the simulated debris flow extent of Xi = 87.5 m/s^2 (the GHD-selected value) and 150 m/s^2 (RAMMS, 2022 mid-range value) overlain to highlight the difference. Each pixel is 1 m^2. a) is uphill of Domain Crescent and b) is uphill of Motutara Road. The difference in debris flow extent is mostly less than 1 m (horizontal). Broader, less channelised flows travel slightly further with Xi =150 m/s^2.***


Control – no erosion features active

Highest erosional properties

Lowest erosional properties

Figure D13 *An example of the comparison of the erosional parameters input parameter showing negligible difference between the high and low erosion scenarios, compared with when no erosion features are used.*

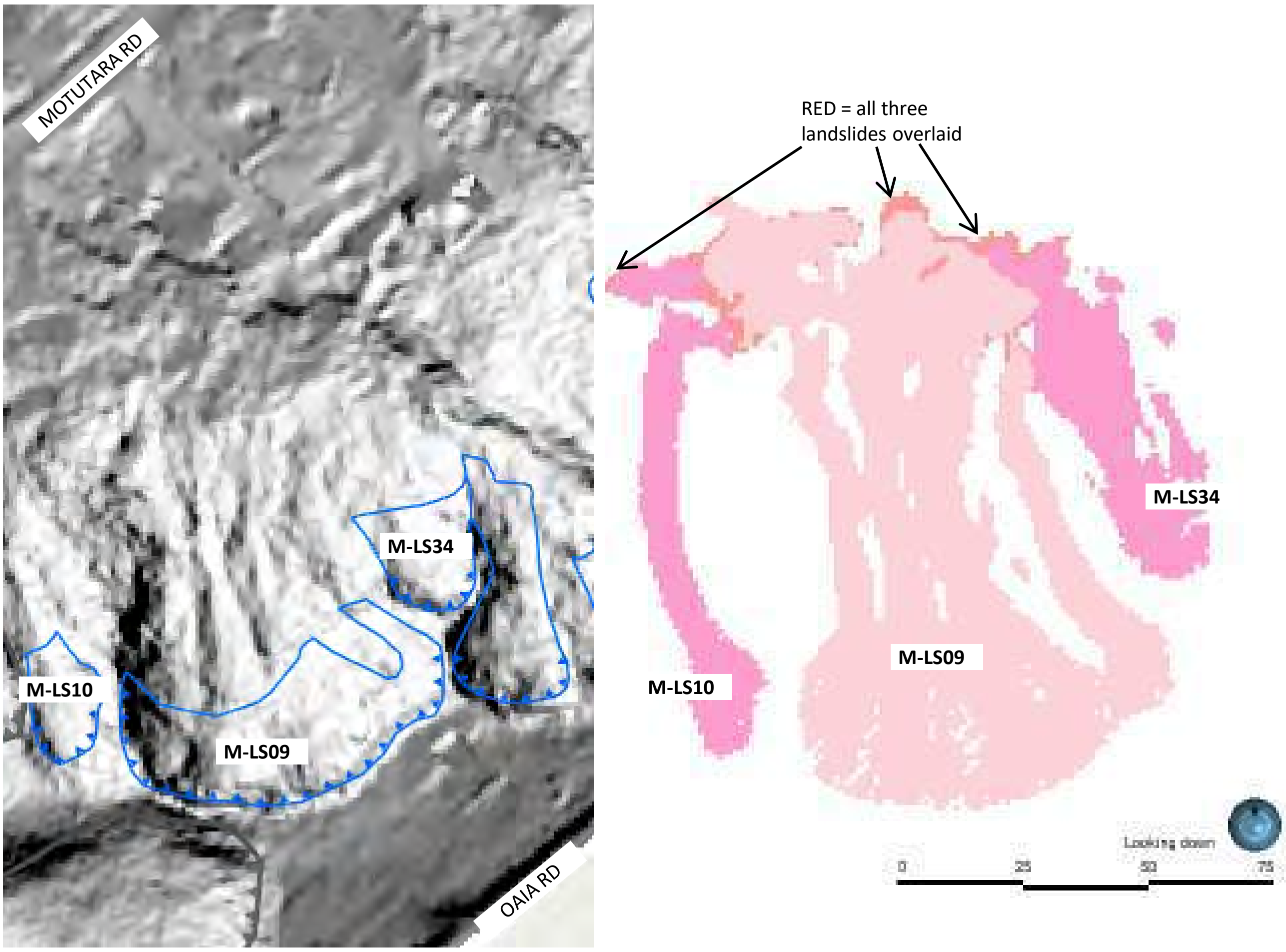


Figure D14 ***Multiple block release versus individual release comparison. The debris flow runout for three landslide sources was simulated individually (light pink and dark pink on the right image), then all three sources were simulated simultaneously (red shading). Each pixel is 1 m^2. This shows that modelling failures from numerous landslides increases the debris flow runout distance only slightly – typically less than 1 m horizontally, but up to 4 m in some areas.***

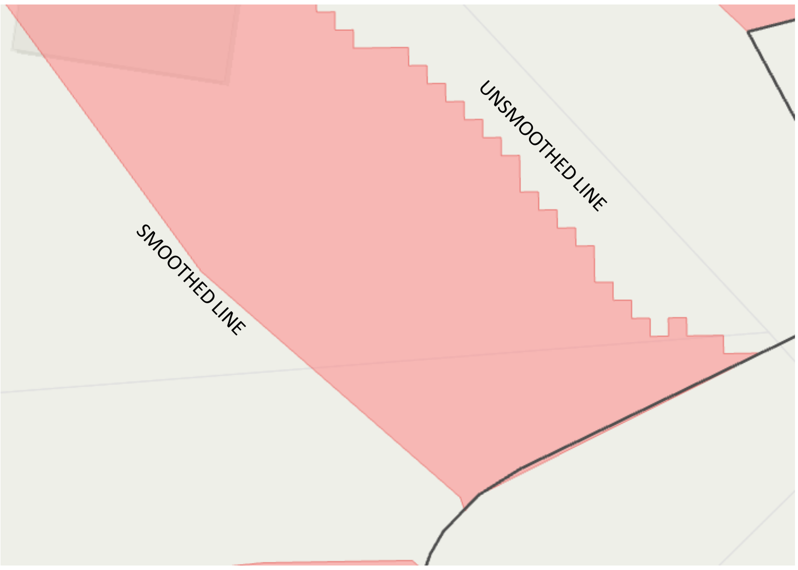


Figure D15 ***Example of where the predicted red debris flow has been manually smoothed (left side) compared with the right side of the red shading, which is the RAMMS output.***

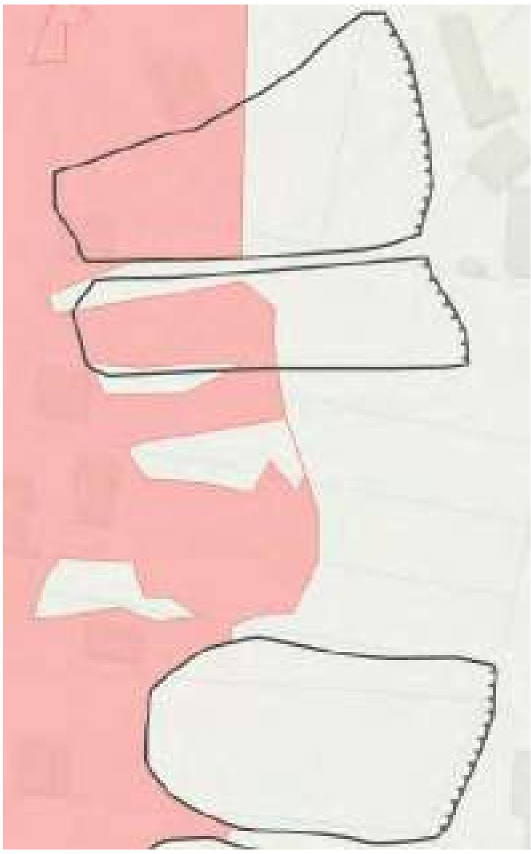


Figure D16 An example of where the red debris flow shading has been removed from the landslide source (bottom of picture), but has been left in when near a dwelling (top of picture)

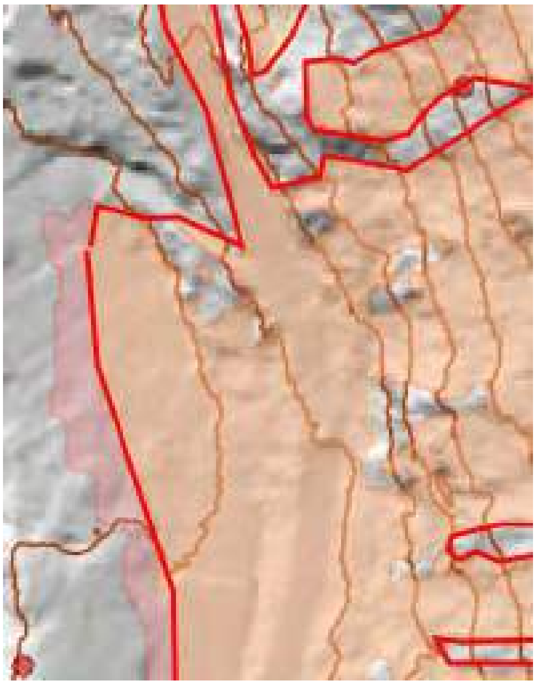


Figure D17 An example of simplification of the predicted debris extent (shown in orange in this work-in-progress example). The thick red line is the edge of the predicted zone in the figures, with the small patches that are less than 0.5 m (shown as grey) not included.

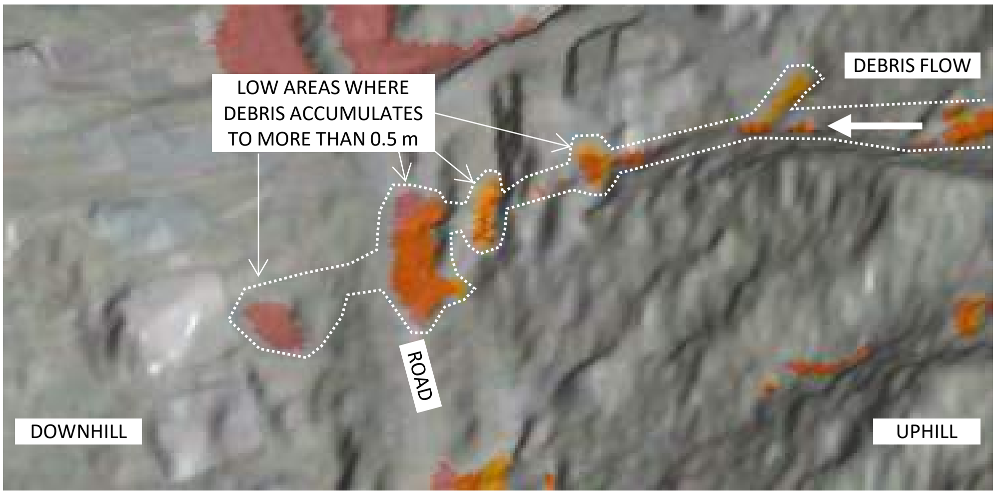


Figure D18 ***An oblique view of predicted debris flow showing how isolated islands can occur due to the highs and lows of the surface topography.***

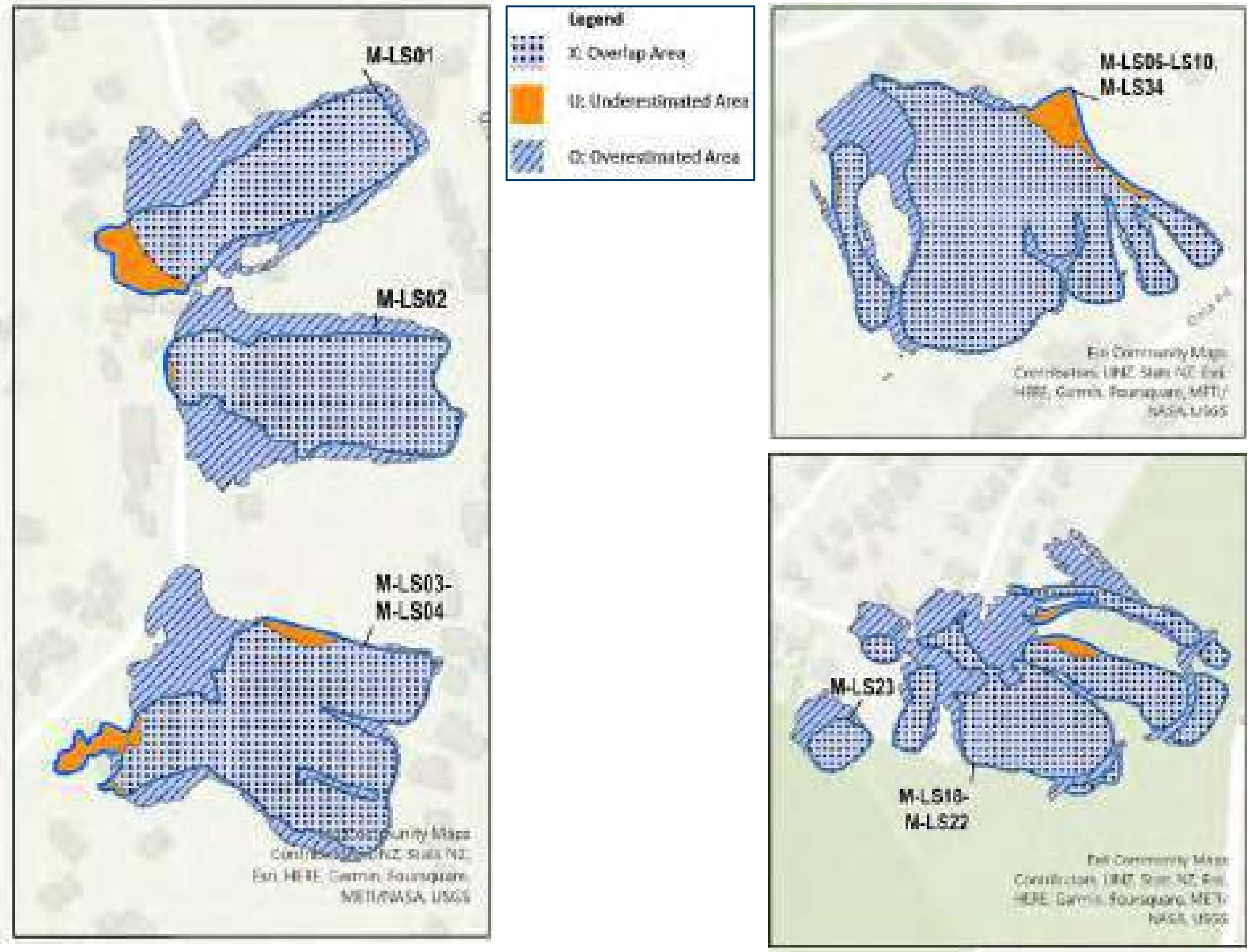


Figure D19 ***Illustration of the area parameters used for calibration quantification***

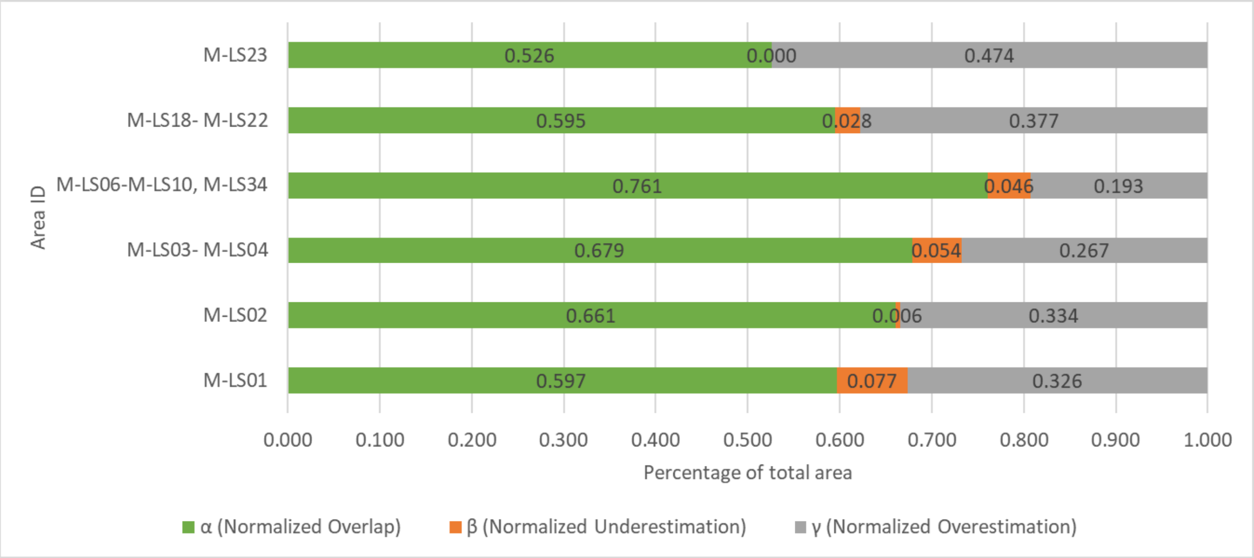


Figure D20 ***Parameters α, β and γ for each landslide***

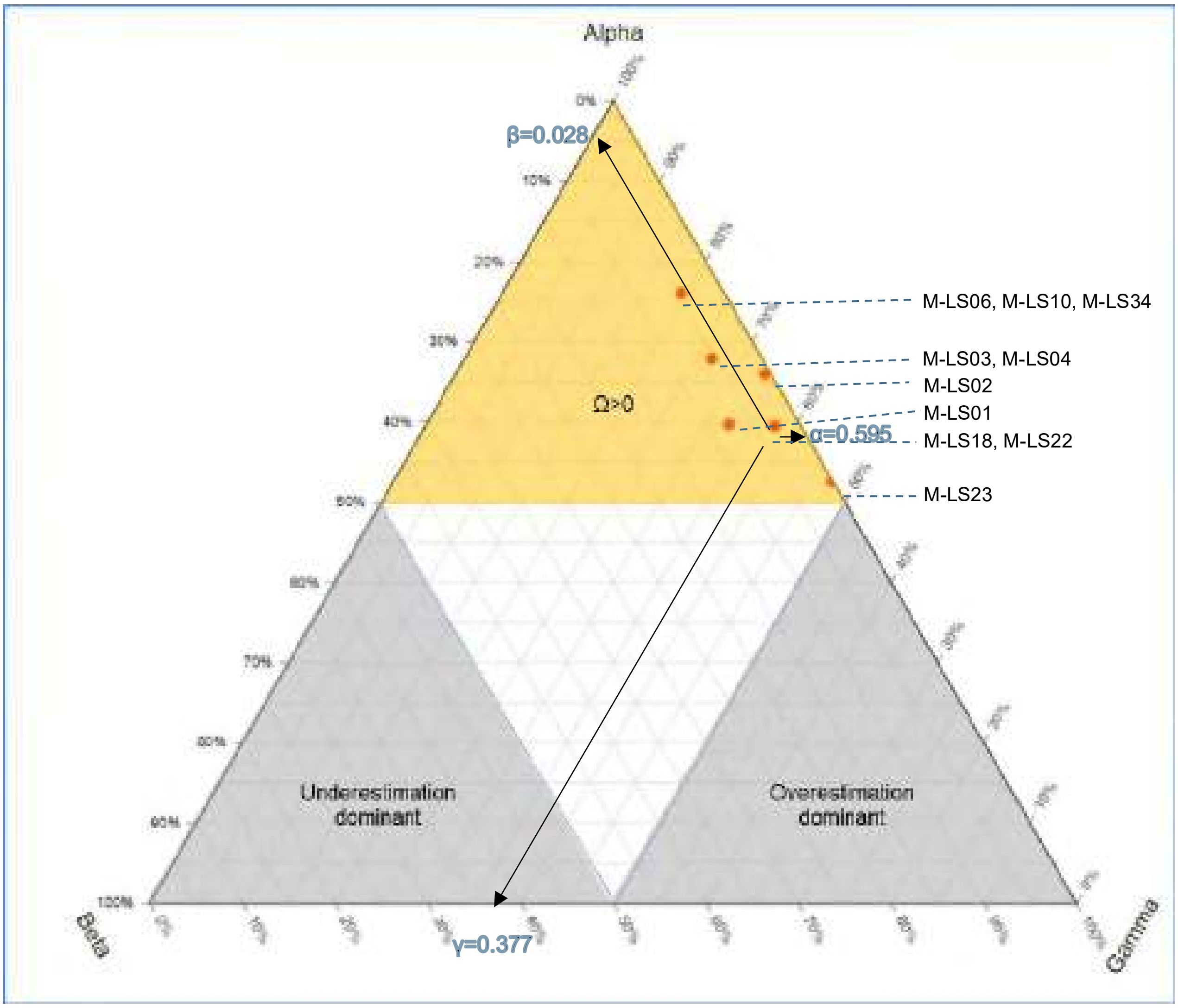


Figure D21 ***Ternary plot showing the debris flow simulated with RAMMS for the observed landslides used for calibration. Note that the latest calibration data is used for the landslides in Zone 5.***