Environment Committee Meeting

17 March 2022

This Report relates to Item 5 in the Agenda

“Estimation of Catchment Susceptibility to Debris Flows and Debris Floods - North Marlborough”

Estimation of catchment susceptibility to debris flows and debris floods–Marlborough Sounds, Pelorus Catchment and Wairau Northbank

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Disclaimer

This report's assessments of debris flow and debris flood susceptibility are not professional assessments of landslide hazards and risks. They are preliminary assessments of debris flow and debris flood susceptibility, using simple methods available to land and resource managers in private and public sectors. Where catchments are mapped as susceptible to debris flows and debris floods, this shows that qualified geoscientists should carry out further detailed investigations to assess landslide hazards and risks for sites within the catchment.

Executive Summary

Background and Objectives

The Marlborough District Council holds responsibilities under section 6 of the Resource Management Act 1991 to manage significant risks from natural hazards as a matter of national importance. This current work was commissioned following the capture of large areas of LiDAR data as part of a nationwide scheme. This data has enabled more detailed analysis of catchment morphology than was previously possible and enabled this current work. This detailed analysis was first proposed as a tool to help guide forestry harvest planning and management but it was quickly realised the resulting tool could be useful in screening for hazards for other land uses.

The purpose of this study is to provide a detailed map of debris flow and debris flood susceptibility to further Marlborough District Council's understanding of landslide hazards within a defined study area. The study area (344,873 ha) comprises the entirety of the District north of the Wairau River and east of the Goulter River, i.e. the Marlborough Sounds, the Pelorus| Te Hoiere Catchment and Wairau Northbank.

This objective required us to develop GIS methods that identified sub-catchments susceptible to debris flows and debris floods while meeting the following criteria:

- Analysis should be rapid and cost-effective
- Analysis should cover a regional area while segmenting larger catchments into sub-catchments to identify variation in debris flow and debris flood susceptibility within the larger catchments.
- Analysis should classify sub-catchments as susceptible to "debris flow" or "debris floods" without evidence from previous events. This is necessary because such events occur infrequently, so there may be no historical record of events occurring in a susceptible catchment, and geomorphological evidence for past events may be difficult to find.

The resulting data layer (map) is intended to inform landowners or prospective land developers on the potential susceptibility of upslope land to failure and production of debris flows or floods. The data layer is not intended as a definitive regulatory tool, nor is it

intended for use on property LIMS. The data layer is provided for information and to prompt further geotechnical investigation where indicated.

Methods

This study uses the catchment Melton ratio to quantify catchment susceptibility to debris flows, debris floods and "clearwater floods" (floodwaters that carry sediment loads below those required for a debris flood).

The methods and interpretation of results in this report are based largely on recent methods developed by Matthias Jakob, Kris Holm and colleagues at BGC Engineering in British Columbia (referred to as the "BGC" method). Here, Melton ratios are calculated for stream segments or sub-catchments, rather than for entire catchments upstream of an alluvial fan. This results in multiple segments within large catchments, each with a different Melton ratio. This allows a more detailed interpretation of debris flow susceptibility in large catchments with many tributary sub-catchments.

Results and Discussion

Using newly-developed methods, we have been able to produce maps depicting Melton ratio and other catchment characteristics, down to small sub-catchment scales over a large study area. These maps can be interpreted to identify debris flow and debris flood susceptibility in sub-catchments. In some cases, interpretation is straightforward. In others, while susceptibility of catchments is identified, there needs to be further work to estimate downstream runout distances of debris flows and floods.

The maps show debris flow and debris flood susceptibility, but not hazard, which requires an estimated likelihood or frequency of occurrence (return interval). Debris flow and debris flood risk management will require further work on these aspects.

The maps produced in this report can map sub-catchments down to less than 0.5 ha—but the ability of such small areas to generate debris flows is not clear. However, there is evidence that catchments down to ~10 ha in size can produce significant debris flows and debris floods, capable of endangering property and human health and safety. Therefore the hazard posed by small steep catchments needs careful investigation.

While steep catchments with a complete cover of tall woody vegetation have longer average return intervals between landslide events, they may still be susceptible to debris flows. These steep forested catchments need to be included in any debris flow risk management for the study area.

Finally, we outline recommendations for further research, to improve the value of the debris flow and debris flood susceptibility maps as a landslide hazard management tool.

1. Introduction

Marlborough has a large amount of steep land susceptible to erosion. In particular, the Marlborough Sounds area is prone to heavy rainfall and various forms of landslides, with a long history of damage to infrastructure such as roads, houses, power and water. Landslides also deliver large amounts of sediment to sensitive receiving environments such as rivers and the coastal marine area (Swales et al. 2021).

Two specific types of landslides called debris flows and debris floods are especially hazardous in the steep terrain of North Marlborough. Reports by Sutherland (2004), Gray and Spencer (2011), and Boam (2018) provide a detailed description of the impacts of debris flows and debris floods triggered by severe rainfall events in North Marlborough in 2004, 2011 and 2018. Debris flows also occurred in many parts of North Marlborough due to the July 2021 rainfall event, with widespread damage to housing and infrastructure.

What are debris flows and debris floods?

Debris flows and associated debris floods are intense sediment-laden flows that occur in steep catchments when heavy rainfall causes slope failures delivering large quantities of fine sediment to stream channels. This input then causes channel sediments to be mobilised as surges fronted by boulders and trees. These can rapidly move down-channel to fan areas, where they can be highly destructive (Figure 1).

Peak flow rates of debris flows can be many times higher than ordinary flood flows because debris flows travel in surges, whereas debris floods do not surge but have peak flows two times higher than floods under equivalent conditions (Wilford et al. 2004). The destructive nature of debris flows is best appreciated by watching videos of debris flows in action.[1]

Property damage commonly results where settlements or infrastructure are located in the path of debris flows. Recent examples of damage occurring on a wide scale include Matatā in the Bay of Plenty (McSaveney et al. 2005), Ligar Bay in Tasman District (Page et al. 2012) and the extensive damage to buildings and infrastructure that occurred in North Marlborough during the extreme rainfall event of July 2021. Deaths are less common but have occurred in New Zealand at Peel Forest (1975), Te Aroha (1985), the Lake Daniels hut

[1] (https://www.youtube.com/watch?v=Fsh5E9m3PrM shows footage of the famous Illgraben debris flow in Switzerland).

in the early 1970s, Klondyke Corner (Arthur's Pass) in 1978 and the upper Motueka River, Nelson in 2002 (McSaveney and Glassey, 2002).

Figure 1. Debris flow deposition caused widespread destruction at the Marlborough Sounds (Marlborough District) in July 2021. Logs in this picture originated from regenerating indigenous riparian forest, not from forest harvesting (Marlborough District Council).

Debris flows typically occur only very occasionally in any given catchment, perhaps once every few decades or centuries, and society is thus largely unaware of the existence of this hazard until it manifests itself as a disaster. Particularly in countries like New Zealand, which have short histories of European occupation, the rapid expansion of land use into hitherto-unutilised steepland areas means that debris-flow hazards are unknowingly created. Consequently, future disasters are inevitable unless debris-flow susceptible areas can be identified, allowing prudent management of debris-flow risks.

Brief for this study

The Marlborough District Council (MDC) holds responsibilities under section 6 of the Resource Management Act 1991 to manage significant risks from natural hazards as a matter of national importance. Under the Act, a natural hazard is defined as an "*earth-*

related occurrence including…landslip,…the action of which adversely affects or may adversely affect human life, property or other aspects of the environment". Part of the Council's role under section 30 (1c) of the Act is to control the use of land to avoid or mitigate natural hazards. In order to fulfil this role, section 35 requires Councils commission such research as necessary to effectively carry out its obligations. This current work was commissioned following the capture of large areas of LiDAR data as part of a nationwide scheme. This data has enabled more detailed analysis of catchment morphology than was previously possible and enabled this current work.

These statutory obligations have led to MDC requesting an assessment of debris flow and debris flood hazards using a newly available LiDAR point cloud covering the entirety of the District north of the Wairau River and east of the Goulter River, i.e. the Marlborough Sounds, the Pelorus| Te Hoiere Catchment and Wairau Northbank ("the study area", Figure 2). The purpose of this new assessment is to provide a map of debris flow and debris flood susceptibility to further the Council's understanding of landslide hazards within the study area.

The maps are provided as geospatial layers in ArcGIS and Google Earth format. They are designed to be easily used by planning and land use professionals to make a preliminary assessment of debris flow susceptibility anywhere in the study area.

This report's assessments of debris flow and debris flood susceptibility are not professional assessments of landslide hazards and risks. They are preliminary assessments of debris flow and debris flood susceptibility, using simple methods available to land and resource managers in private and public sectors. Where catchments are mapped as susceptible to debris flows and debris floods, this shows that qualified geoscientists or geotechnical engineers should carry out further detailed investigations to assess landslide hazards and risks for sites within the catchment.

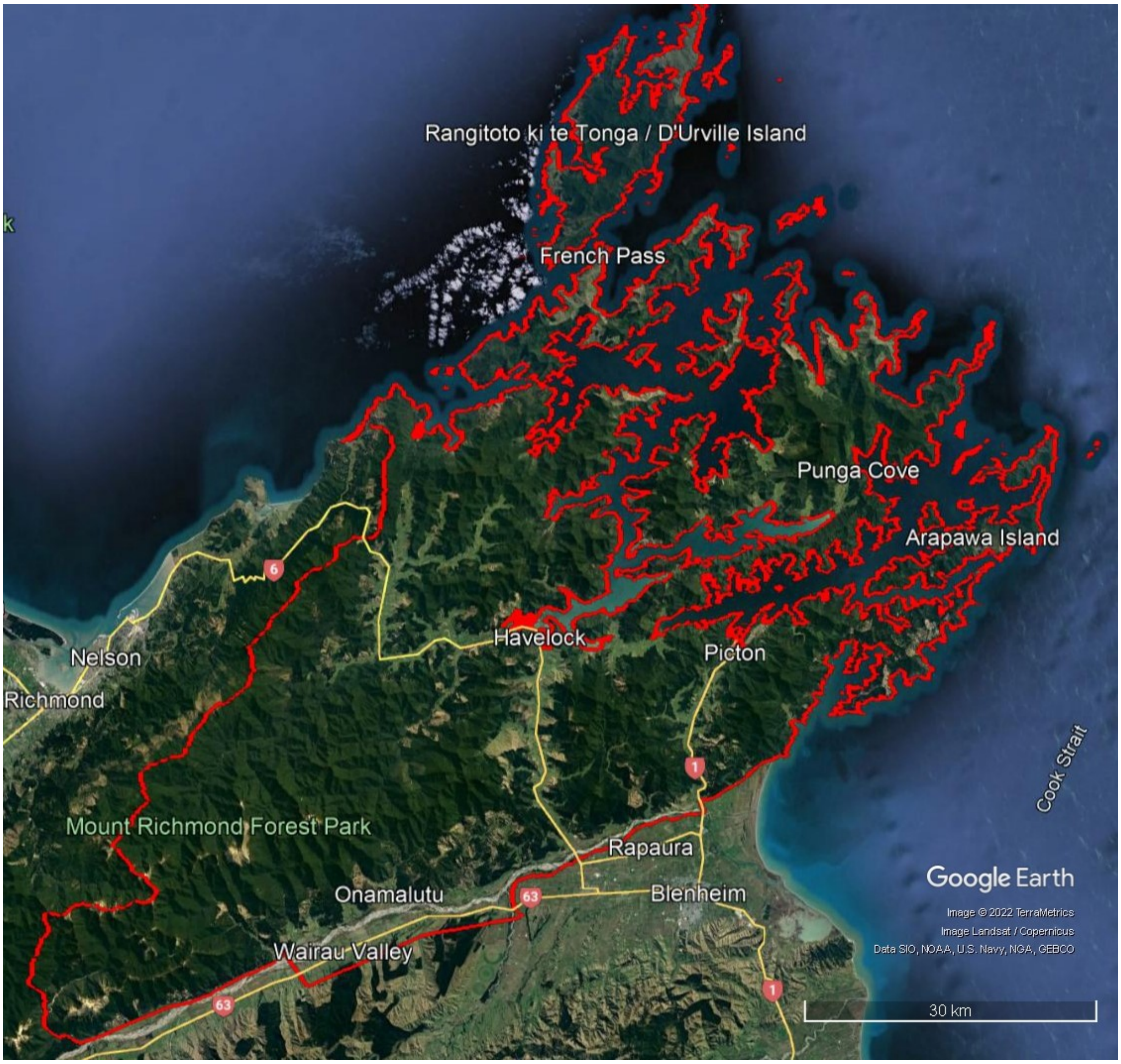

Figure 2. The area covered by this study includes all parts of Marlborough District, north of the main stem of the Wairau River and east of the Goulter River.

2. Background and Research Objectives

2.1 Background

The Melton Ratio

This study uses the catchment Melton ratio to quantify catchment susceptibility to the range of hydrogeomorphic process types—debris flows, debris floods and "clearwater floods" (floodwaters that carry sediment loads below those required for a debris flood). It seeks to classify sub-catchments as susceptible to "debris flow" or "debris floods" without evidence from previous events. This is necessary because such events occur infrequently, so:

1. there may be no historical record of events occurring in a susceptible catchment, and
2. geomorphological evidence for past events may be obscured by subsequent deposition from clearwater floods or by development, e.g. contouring or rock picking that removes levees, uneven land surfaces, small boulders and other indicative features.

The Melton ratio corresponds to the ratio between watershed relief and the square root of watershed area (Melton 1957). Figure 3 shows the most common method for estimating the Melton ratio, where it is calculated for an entire catchment above the apex of the fan onto which a debris flow would discharge.

The Melton ratio is an appropriate screening level indicator of a catchment's propensity (or susceptibility) to produce debris floods or debris flows (Wilford et al., 2004). However, these two erosion process types should be viewed as a continuum and can occur within the same watersheds at different return periods and in different stream channel segments.

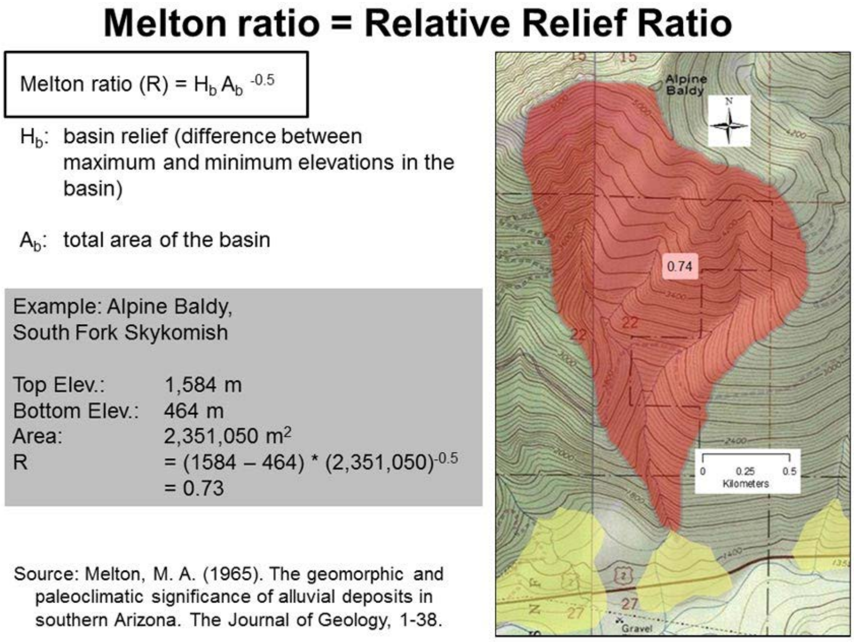

Figure 3. Calculation of the Melton ratio for a steep catchment above an alluvial fan. https://www.kingcounty.gov/services/environment/water-and-land/flooding/maps/river-landslide-hazards/mapping-methodologies.aspx, downloaded 1 March 2021.

Note that the Melton ratio is an index of a catchment's susceptibility to debris flows and debris floods but does not assess debris flow hazards. Debris flow occurrence depends on three factors (Welsh and Davies 2010):

1) availability of large volumes of sediment for mobilisation, either on slopes or in a stream channel;
2) steep slopes combined with
3) rainfall and/or streamflow of sufficient intensity to mobilise the sediment.

The Melton ratio focuses on the second factor (slope steepness), recognising that large volumes of sediment and landslide-triggering rainfall events are also needed to meet the conditions for a debris flow. Sediment availability and rainfall event size/probability need to be combined with the Melton ratio to be able to assess debris flow hazards. For this reason, the Melton ratio does not reflect vegetation cover, as this influences debris flow hazard through its effect on landslide susceptibility and sediment supply.

The "BGC" analytical approach

The methods and interpretation of results in this report are based largely on recent work by Matthias Jakob, Kris Holm and colleagues at BGC Engineering in British Columbia (see Holm et al. 2016, Sturzenegger et al. 2021). These will collectively be referred to as the "BGC" method.

This work was driven by a major rainfall and flooding event in June 2013 in the province of Alberta, Canada, producing one of Canada's most expensive natural disasters with about CDN $6 billion in damage. Debris flows and debris floods caused extensive highway closures and damage to development on alluvial fans. The Government of Alberta requested an inventory of all fans intersecting towns and roads potentially subject to debris flow, debris flood or flood hazards. Zones susceptible to debris flow and debris-flood initiation were identified semi-automatically based on stream segments in a two-step process: stream segment delineation and classification. Once delineated, the stream segments were classified to differentiate those most likely to generate debris flows from those most likely to generate debris floods (Holm et al. 2016). These process types were differentiated using two geomorphometric metrics, the Melton ratio and watershed length, using thresholds defined by Holm et al. (2016) and shown in Table 1. The watershed length (WL) was calculated as the total channel length upstream of a given stream segment to the stream segment farthest from the fan apex.

Table 1. Thresholds for stream segments without a defined fan (Holm et al. 2016)

Process Type	**Melton Ratio**	**WL (km)**
Clear-water flood	<0.2	All
Debris flood	0.2-0.5	All
Debris flood	>0.5	> 3 km
Debris flow	>0.5	≤ 3km

Note that this work differs from previous studies using the Melton ratio in two respects:

1. Thresholds between clear-water floods, debris floods and debris flows were set using more conservative Melton ratio values of 0.2 and 0.5, rather than 0.3. and 0.6 commonly used in other studies.

2. Melton ratios were calculated for stream segments rather than entire catchments upstream of the alluvial fan subject to debris flows and floods. This resulted in multiple segments of large catchments, each with a different Melton ratio (Figure 4).

Figure 4. The influence of catchment size on predicted stream landslide and flood processes for a catchment in Alberta, Canada. Here individual Melton ratios are calculated for stream segments within the larger catchment. Brown=debris flow susceptible, green=debris flood susceptible, blue=not susceptible to debris flows or debris floods. Holm et al. (2016)

In our study, we used the BGC method to overcome a limitation of the Melton analysis, where Melton ratios for large catchments (defined using the criterion of WL>2.7 km (Wilford et al. 2004)) may not be reliable indicators of debris-flow susceptibility. The advantage of the BGC method is that within a large catchment (WL>2.7 km), sub-catchments with WL<2.7 km and high Melton ratios can be reliably identified as susceptible to debris flows or debris floods.

We deviated from the BGC method in two respects:

1. We did not use the BGC Melton ratio thresholds, shown in Table 1. Instead, we used widely published thresholds for differentiating catchments susceptible to clearwater floods, debris floods and debris flows (Melton ratios <0.3, 0.3-0.6 and >0.6 respectively). However, because we calculated actual Melton ratios for every sub-catchment in the study area, it would be straightforward to re-classify catchments using the BGC thresholds.
2. BGC consider that any catchment > 3km is not susceptible to debris flows, even where its Melton ratio is >0.5 (Table 1). Experience with New Zealand debris flow events, e.g. Ligar Bay in 2011 (Page et al. 2012, Bloomberg and Palmer 2021a) and Matatā (Welsh and Davies 2010) shows that large catchments with WL>2.7 km can develop debris flows even when their Melton ratios are <0.5-0.6. Therefore, we do not rule out debris flow susceptibility in large catchments. This point is discussed further in Section 5.2.

2.2 Research Objectives

The purpose of this assessment was to provide a map of debris flow and debris flood susceptibility over a large study area to further MDC's understanding of slope instability hazards within that area. The study area comprised all catchments in Marlborough District to the north of the main stem of the Wairau River and east of the Goulter River (Figure 2).

This objective required us to develop GIS methods that identified sub-catchments susceptible to debris flows and debris floods while meeting the following criteria:

- analysis should be rapid and cost-effective
- analysis should cover a regional area while segmenting larger catchments into sub-catchments to identify variation in debris flow and debris flood susceptibility within the larger catchments.

3. Methods

To meet the research objectives, we developed a computationally fast and efficient method for assessing Melton ratio values occurring within sub-catchments of a watershed. The reason for developing this approach was to estimate Melton ratios over a large study area. Watershed Melton ratio modelling requires defining a fan apex or depositional area above which we calculate the watershed relief and area (Melton ratio=relief/area$^{0.5}$) to provide information around debris flows and floods. In contrast, the "BGC" approach estimates Melton ratios for sub-catchments (segments) within a watershed. Our mapping shows sub-catchments down to sizes of ~0.5ha.

Note that when calculating the segmented sub-catchment Melton ratios, we have not identified the fan apex or depositional locations for a sub-catchment but instead allowed the sub-catchments to be automatically assigned to the next highest-order stream to which they contribute.

Catchment delineation

Here we describe the simple method for estimating sub-catchment susceptibility for debris flows and debris floods. We analyse a digital elevation model (DEM) using a geographical information system (GIS) and Python script. The use of GIS means that catchments can be rapidly classified using a 10-m cell size resolution DEM on a desktop basis, covering areas up to 30 km by 30 km in a single workflow. A 10-m Digital Elevation Model (DEM) was developed by MDC from the latest point cloud acquisition of LiDAR data. A 10-m DEM provides a compromise between providing enough detail for sub-catchment area and relief definition and the ability to develop Melton ratios across large areas and within realistic computational timeframes for raster analysis.

The work was undertaken using Python version 2.7.16 (Python Software Foundation), libraries from ArcGIS version 10.8, and ARC Hydro tools version 10.8.

The python script workflow initially removes sinks and pits (a cell or set of spatially connected cells whose flow direction cannot be assigned one of the eight valid values in a flow direction raster) using the fill command in the Arc Hydro Tools. The resulting hydrologically sound DEM is used to develop flow direction, flow accumulation, and catchment segment development. The stream network is developed by defining upslope catchment areas (above which streams are considered to cease). Flow accumulation of fewer than 100 cells was used as the threshold for stream network initiation. Stream order using the Strahler system was also developed before converting these rasters to polylines. A conditioning algorithm is used to "burn-in" streams across the DEM to ensure catchment delineation. The “Catchment Grid Delineation” function in ArcHydro Tools was applied to define individual catchments. This approach develops a grid where cells contributing to each catchment are identified. Sub-catchments are delineated using the stream definition, stream segmentation and drainage line processing modules from Arc Hydro Tools Python. For details, refer to Arc Hydro Tools Manual (http://downloads.esri.com/archydro/archydro/tutorial/doc/arc%20hydro%20tools%202.0%20-%20tutorial.pdf).

Calculation of sub-catchment characteristics and Melton ratios

Once the sub-catchments are defined, sub-catchment characteristics and Melton ratios are calculated from the original 10-m cell size resolution DEM to ensure calculations are undertaken from original values representing the true landscape.

Holm et al. (2016) and Sturzenegger et al. (2021) applied Melton analysis to catchment segments, bounded at their lowest point by chosen “pour points” in a catchment stream network. The chosen pour point (A in Figure 5) is defined as the “node” at the downstream end of a stream segment (A-B in Figure 5), representing the reach defined by that segment. The Melton ratio for each catchment segment is calculated considering (1) the total watershed area contributing water to the downstream end of the segment and (2) the relief between this downstream end of the segment and the highest point of the contributing watershed.

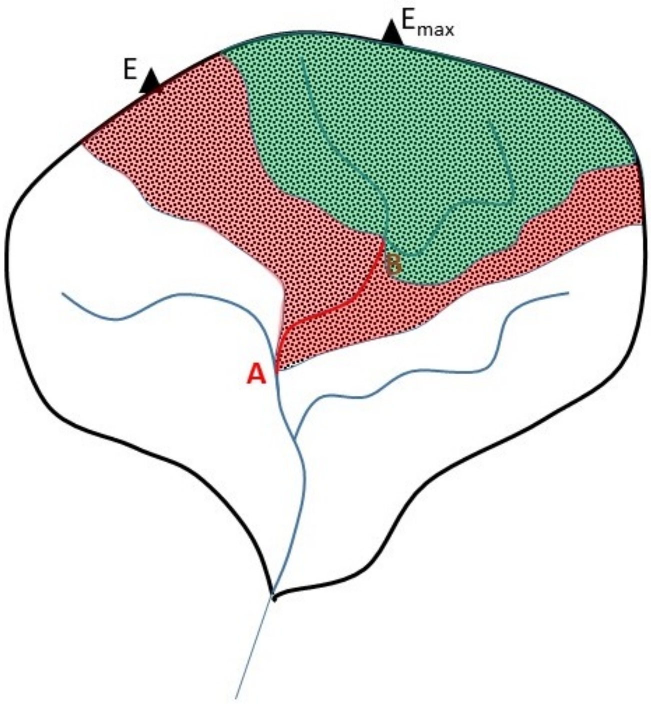

Figure 5. The figure shows the calculation of Melton ratio R for catchment segments. Source: Tim Davies, pers. comm.

Here, E_{max} is the maximum catchment elevation, E is the maximum elevation of the pink sub-catchment that feeds segment AB directly, and E_A and E_B are elevations at A & B.

In the model used by Holm et al. (2016) and Sturzenegger et al. (2021),

$R_A = (E_{max} – E_A)/\sqrt{(\text{area of pink and green})}$ and $R_B = (E_{max} – E_B)/\sqrt{(\text{area of green})}$

Where R_A is the Melton ratio for the combined pink and green sub-catchment, and R_B is the Melton ratio for the green sub-catchment.

4. Results

The outputs are in the form of geospatial layers showing the stream courses and/or sub-catchment boundaries, sub-catchment size (WL and area) and the Melton ratios of sub-catchments.

Sub-catchments can be classified in terms of their debris flow and debris flood susceptibility according to Table 2. Where WL>2.7 km, sub-catchments may still generate debris flows, but their Melton ratio may not be a reliable indicator of debris flow susceptibility.

Table 2. Thresholds for stream segments without a defined fan, and WL<2.7 km

Process Type	**Melton Ratio**
"Clear-water" flood	<0.3
Debris flood	0.3-0.6
Debris flow	>0.6

The creation of the sub-catchments was demanding in terms of computer time. Therefore, the geospatial layer was broken into 20 "tiles" covering approximately 2935-37,625 ha each (Table 3, Figure 6).

The geospatial layers for the tiles are provided in ArcGIS format, allowing further analysis of the data and presentation in various formats. Also provided is a kmz layer for each tile, allowing easy visual exploration of the sub-catchments and their Melton ratios using Google Earth. These are provided in an electronic appendix to this report (Appendix E-1, "Map Deliverables"). To show the nature of the map outputs, part of Tile 10 is shown in Figure 7. This map covers the Graham River catchment, which discharges into Whatamango Bay immediately to the east of Waikawa and Picton, in the Marlborough Sounds.

Table 3. Areas of “tiles” used for geospatial analysis (see Figure 6 for the location of “tiles”)

Tile ID	**Geographic name**	**Area (ha)**
Area 1	Onamalutu	36,651
Area 2	Wakamarina	30,626
Area 3	Upper Pelorus	37,625
Area 4	Rai Valley	21,086
Area 5	Beatrix Bay-Waitata Reach	3,674
Area 6	Kaiuma-Okiwi Bays	28,713
Area 7	D’Urville Island	17,009
Area 8	Okaramio-Havelock	15,366
Area 9	Pukaka Valley	2,935
Area 10	Picton-Port Underwood-Tory Channel	19,778
Area 11	Grove Arm-Mahakipawa-Mahau Sound	18,377
Area 12	Elaine Bay-French Pass	7,215
Area 13	Kaituna-Tuamarina-Koromiko	24,571
Area 14	Goulter-Top Valley	28,324
Area 15	Arapaoa Island-Blumine Island	8,240
Area 16	Kenepuru Sound-Beatrix Bay	18,536
Area 17	Endeavour Inlet-Cape Jackson	6,279
Area 18	Anakoha-Port Gore	7,853
Area 19	Kenepuru Head-Big Bay	5,711
Area 20	Admiralty Bay-Bulwer	6,304
Total		**344,873**

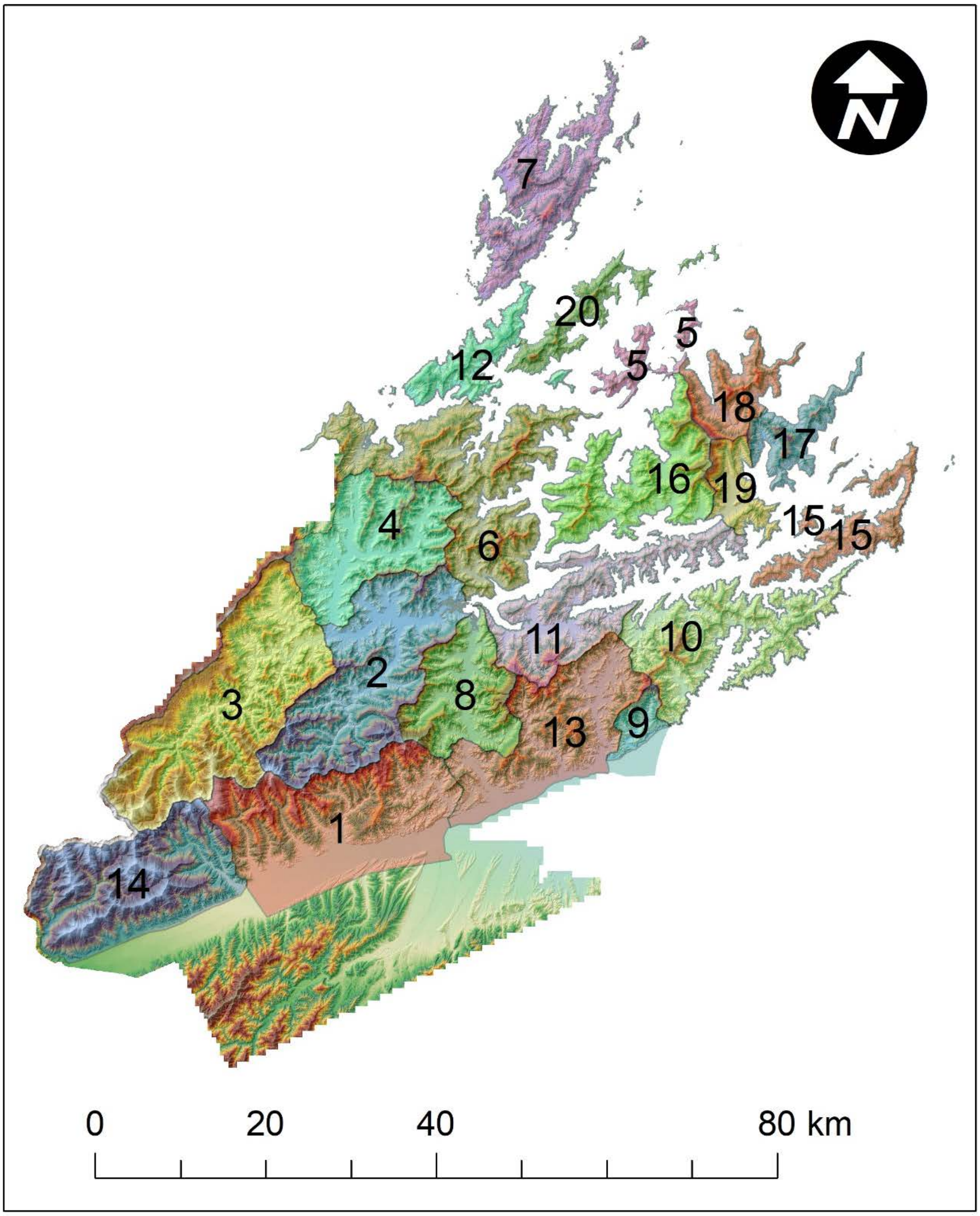

Figure 6. Areas of each of the 20 "tiles" (Areas 1-20) are shown in Table 3. The total mapped area covers 344,873 ha.

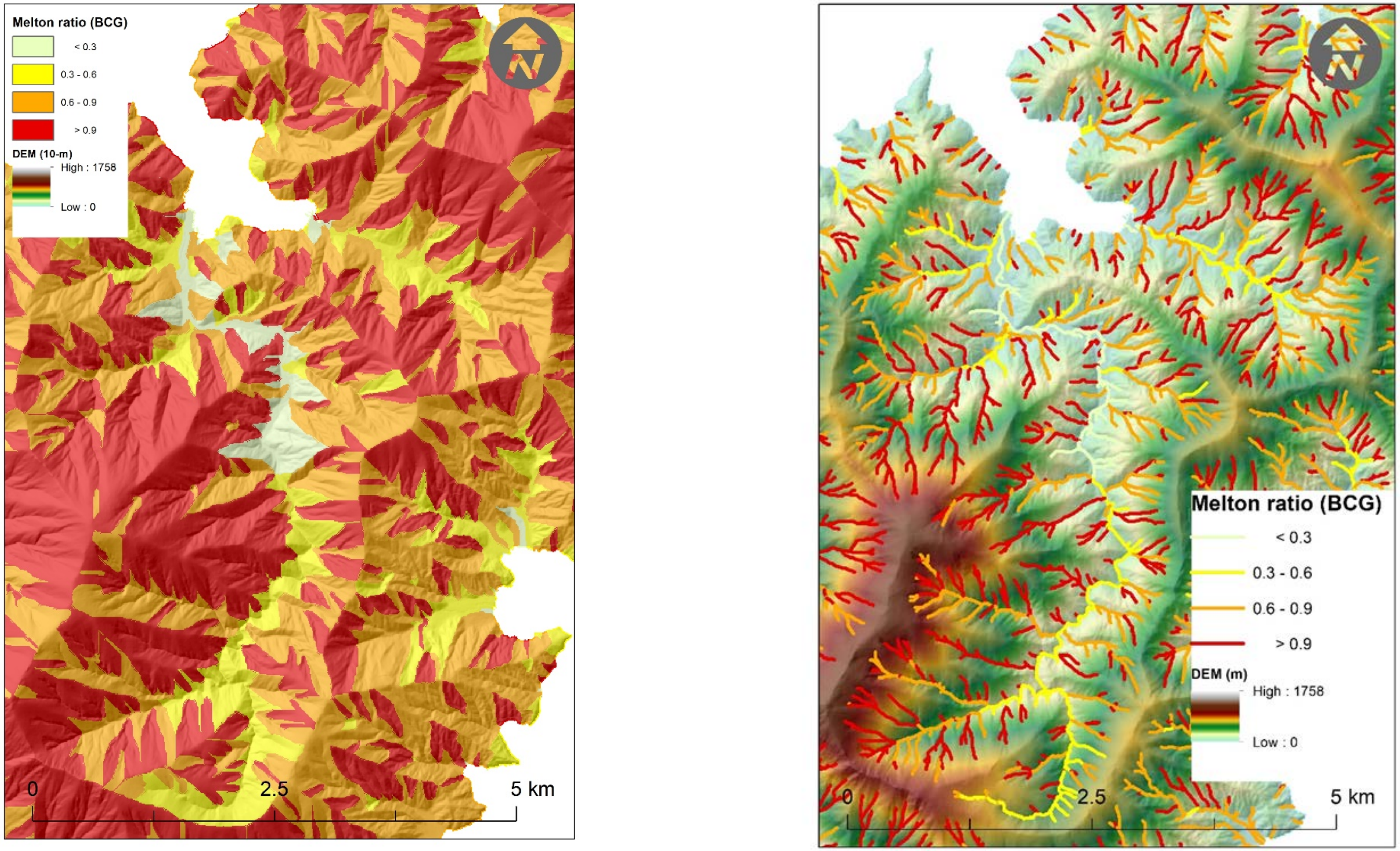

Figure 7. Catchment Melton ratios for Whatamango Bay and the Graham River catchment using the BGC method. The left-hand figure shows sub-catchment Melton ratios by the colour of each delineated sub-catchment. The right-hand figure shows each sub-catchment stream channel, colour-coded according to its Melton ratio.

5. Discussion

5.1 Limitations of the Melton ratio for estimating hazard from debris-flows

The Melton ratio has limitations as an indicator of debris flow hazards. Sturzenegger et al. (2021) note that "*Hydrogeomorphic process types predicted from watershed morphometry are subject to limitations. In particular, the classification describes the potential process type but does not consider the geomorphic or hydroclimatic conditions needed to actually generate events.*"

Therefore, the Melton ratio can indicate sub-catchment debris flow/debris flood susceptibility[2] but cannot indicate the debris flow or debris flood hazard since hazard assessment must include an estimated likelihood or frequency of occurrence (return interval) as well as magnitude or severity. Estimation of frequency is notoriously difficult for debris flows, which in many cases occur with return intervals of several centuries or longer. This is because in most cases, debris flow occurrence is "supply limited"[3]—the soil-rock mantle in a catchment will first need to "ripen", i.e., accumulate a sufficient depth of weathered potentially-mobile material so that a large enough volume of landslide debris can reach the stream channel to support initiation of a debris flow. Thus, debris flows can be infrequent and, for any individual landslide-triggering rainfall event, widely dispersed.

For example, the 2011 debris flow event at Ligar Bay was estimated as having a return interval of 200 years (Page et al. 2012). This hazard level is unacceptably high (Page et al. 2012) since it implies that any house in the debris flow path has an annual exceedance probability of 0.005 of being seriously impacted by debris flows. This equates to a probability of 0.22 of serious impacts over the 50-year design life of a house.

In conclusion, debris flow hazards are difficult to assess and even more difficult to plan for since their low frequency means there are few or zero observations of hazards for a specific location. As a result, communities may not have a realistic understanding of the potential consequences.

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[2] The term "landslide susceptibility" is defined by Fell et al. (2008) as "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."

[3] Globally, there are few examples of supply-unlimited catchments (famous examples occur in China and Switzerland).

5.2 Limitations of the Melton ratio in large catchments or catchments with atypical geomorphology

The Melton ratio is a useful indicator of debris-flow susceptibility for steep smaller catchments (WL< 2.7 km, (Wilford et al. 2004), where WL is measured on a straight line from fan apex to the catchment head). However, the Melton ratio for a larger catchment is problematic in at least two cases:

- When catchments are large (>2.7 km length) with steep land catchments in the headwaters and easier relief at the front of the catchment, debris flows may be generated in steep headwaters or tributary sub-catchments in these larger catchments. The circumstances under which these debris flows may propagate through lower parts of the catchment, with shallower stream gradients, are unclear.
- Similarly, the overall catchment Melton ratio may not be a good indicator of debris-flow susceptibility in catchments with low relative relief yet steep tributary streams due to downcutting into a plateau landform. This was the case for the Awatarariki Catchment at Matatā in the Bay of Plenty. This catchment has a Melton ratio of 0.17, with WL=3.4 km. Nonetheless, it generated a disastrous debris flow in 2005 (McSaveney et al. 2005).

The discussion below covers examples from the study area where the interpretation of the Melton ratio is straightforward and two where it is not. All examples occur within the Graham River catchment, which discharges into Whatamango Bay immediately to the east of Waikawa and Picton, in the Marlborough Sounds (Figure 8). Here, interpretation of Melton ratios for short coastal sub-catchments discharging into Whatamango Bay is straightforward. However, interpretation of the Melton ratios for the headwaters sub-catchments of the Graham River is not.

The left-hand map in Figure 8 shows Melton ratios calculated for sub-catchments defined as the entire watershed area above an alluvial fan (Bloomberg and Palmer 2021b). Thus, large headwaters sub-catchments such as 64 (WL=4.4km) have a Melton ratio of 0.28, indicating marginal susceptibility to debris floods but not debris flows below the apex of the alluvial fan at the base of this sub-catchment.

The right-hand map in Figure 8 shows the same area, with sub-catchments identified using the BGC method. Here it is clear that there are numerous tributary sub-catchments within sub-catchment 64, which are susceptible to debris flows.

As with the Awatarariki catchment at Matata, interpretation of the Melton ratios for these smaller tributary sub-catchments is not straightforward. Their sub-catchment BGC Melton ratios suggest that debris flows could occur, down as far as the blue arrow in the right-hand image of Figure 8. The susceptibility of the catchment to debris flows below that point would need further detailed analysis of debris-flow runout distances. This is because the sub-catchment BGC Melton ratio is 0.283 below the blue arrow—suggesting that debris flows or even debris floods would likely run out and not propagate beyond that point.

Therefore the potential for transport of debris flow material downstream from the alluvial fan at the base of sub-catchment 64 would need further detailed analysis by expert geoscientists. As noted by Welsh and Davies (2010) concerning Matatā:

"It is thus likely that other factors such as the local topography near the drainage point of the watershed and sediment supply conditions are more important controls on the potential for debris flows in these watersheds. For example, examination of the DEM for Awatarariki Stream watershed shows a number of small tributaries to lie adjacent to each other and in relatively close proximity to the fan. Rainstorm-generated debris flows in these tributaries may thus have potential to coalesce at stream junctions (as was the case in the 2005 event; McSaveney et al. 2005). This may have the effect of forming one large debris flow capable of flowing further than any flow on its own."

These comments also apply to sub-catchment 102. Despite having a WL of only 1376 m, its Melton ratio of 0.38 at the apex of its alluvial fan needs to be weighed against the high debris flow-susceptibility of many of its tributary sub-catchments.

In contrast, the interpretation of the Melton ratios for the numerous small sub-catchments discharging directly into Whatamango Bay is straightforward. Comparison of the two maps in Figure 8 shows that Melton ratios for these small sub-catchments are similar (with allowance for the left-hand map being developed from a 1-m DEM vs a 10-m DEM for the right-hand BGC map). In almost all cases, both methods classify these sub-catchments as susceptible to debris flows (Melton ratio > 0.6).

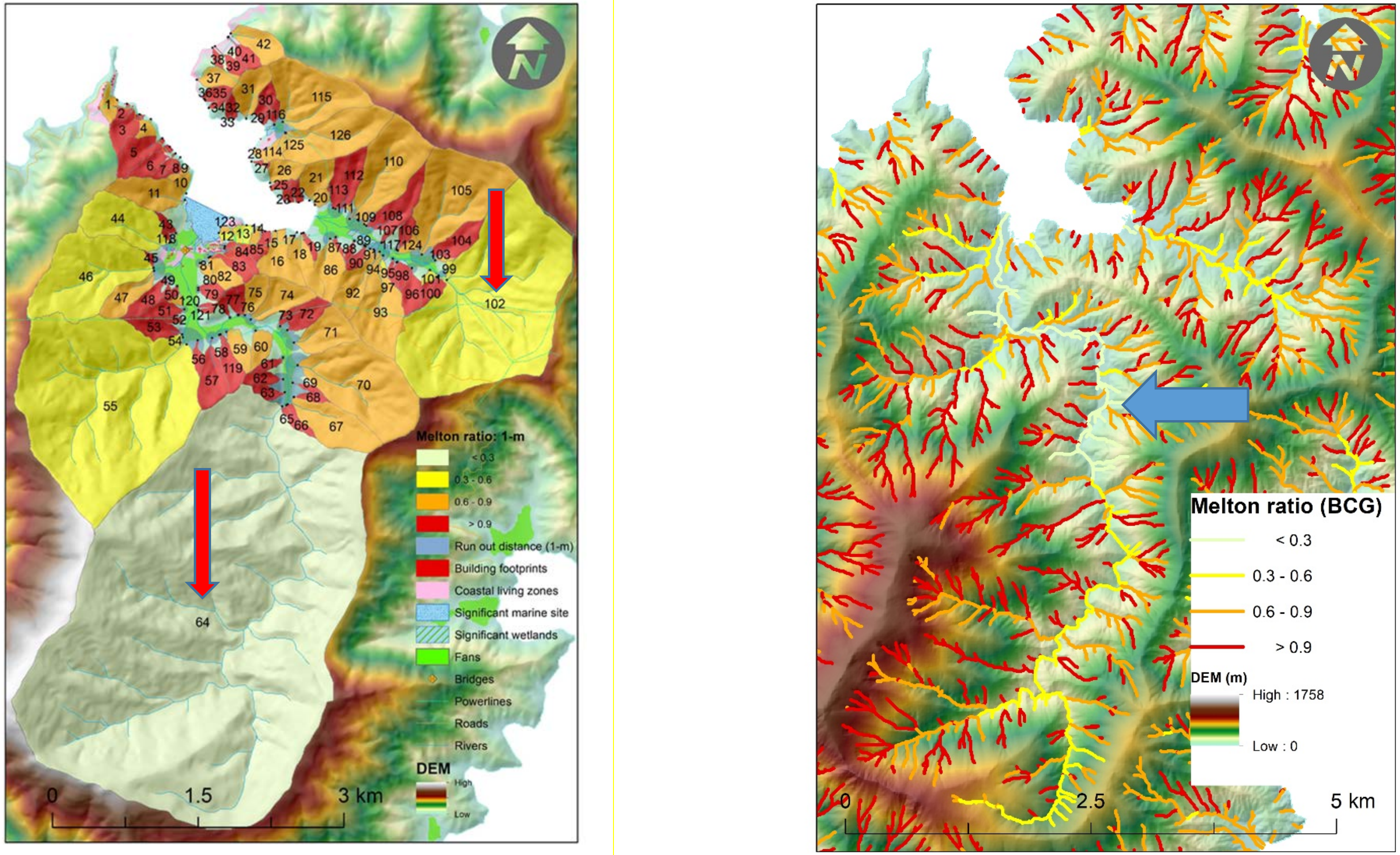

Figure 8. The left image shows Melton ratios calculated for sub-catchments defined as the entire watershed area above an alluvial fan. (Bloomberg and Palmer 2021b). The red arrows show catchments 64 and 102 (discussed in the text). The right-hand image shows the same area, with sub-catchments identified using the BGC method. The blue arrow is a suggested limit for debris flows in the main catchment.

5.3 Effect of catchment and debris flow size

Using a 10-m DEM with high resolution allowed small sub-catchments to be identified and analysed down to a size of ≤0.5 ha. However, it is not clear that catchments of this size can generate significant or dangerous debris flows. Small debris flows are under-researched, possibly because the consequences are not large enough to attract the attention of researchers.

This issue has been investigated by Marchi et al. (2019) and de Haas & Densmore (2019). The data from both papers extend down to a minimum catchment size of ~10 ha. Both papers report a median debris flow volume of ~100-300 m^3 for the smallest catchments in their data. These volumes are within Size class 1 of Jakob's (2005) classification (Table 4).

Table 4. Jakob's (2005) classification of debris-flow volume and area inundated. Classes 1-4 are relevant to bouldery debris flows in steep NZ catchments. Class 5 to 10 are volcanic debris flows where large areas (entire floodplains or mountain forelands) are inundated.

Size class	Volume (m^3)	Area inundated	Potential consequences
1	$<10^2$	<400 m^2	Very localised damage, known to have killed forestry workers in small gullies, damage small buildings
2	10^2 to 10^3	400-2000 m^2	Could bury cars, destroy a small wooden building, break trees, block culverts, derail trains
3	10^3 to 10^4	2000 m^2 to 1 ha	Could destroy larger buildings, damage concrete bridge piers, block or damage highways and pipelines
4	10^5 to 10^6	1-4 ha	Could destroy parts of villages, destroy sections of infrastructure corridors, bridges, could block creeks
5-10	10^2 to $>10^9$	>4 ha	Destruction from township to city scale

An example of a small Class 1-2 debris flow that originated from a small catchment <20ha, but damaged a house and an outbuilding, is shown in Figure 9.

Figure 9. A relatively small debris flow originating in a catchment of <20ha nonetheless caused major damage to buildings and resulted in a significant volume of debris running out on the shoreline in Blackwood Bay, Marlborough Sounds (Marlborough District Council, 21 July 2021).

This catchment size issue is relevant to areas such as Ligar Bay in Tasman District. In the 2011 rainfall event, large catchments (up to 276 ha area and WL 3.4 km) in the bay's western end delivered large Class 3 debris flows that ran out for several hundred metres (Bloomberg and Palmer 2021a). In contrast, smaller catchments at the bay's eastern end were less active (Table 5). Nonetheless, catchments as small as 11.7 ha delivered debris floods or debris flows.

Table 5. Catchment characteristics and process types for small catchments at the eastern end of Ligar Bay, 2011 Rainfall event. Debris flow catchments are shaded in grey. Data from Bloomberg and Palmer (2021a).

Catchment	Area (ha)	WL (m)	Max. elevation (m)	Melton Ratio	Runout (m)	Debris flow/flood
1	27.1	700	151	0.27	53	None
2	10.8	575	180	0.5	70	None
3	12.8	604	233	0.6	46	Dflood
4	16.2	763	281	0.65	56	Dflood
5	11.7	704	289	0.77	55	Dflood
6	13.9	684	289	0.73	49	Dflood
7	15.0	655	284	0.68	46	Dflow
8	22.2	832	282	0.55	70	Dflow

In summary, catchments down to 10 ha can still deliver debris flows and debris floods capable of causing damage or posing a risk to human health and safety. However, the susceptibility of individual catchments <10 ha to debris flows or debris floods is unclear.

5.4 Effect of vegetation cover

In Section 2.1, it was noted that the Melton ratio focuses on slope steepness as an indicator of catchment debris flow susceptibility. Debris flow hazard also depends on catchment landslide susceptibility and the likelihood of landslide-triggering rainfall events. The vegetation cover influences debris flow hazard through its effect on landslide susceptibility rather than any influence on the Melton ratio.

So what are the likely effects of vegetation cover on landslide susceptibility (and indirectly, the occurrence of debris flows)? Bloomberg and Davies (2012) reviewed this question and concluded that:

"In the long term, rates of erosion are controlled by geological uplift, as modified by the climate regime and lithology. ***Forested and deforested catchments sharing the same geomorphological characteristics will have the same long term rate of erosion*** (emphasis added)*. In this context, forest soils can be regarded as a reservoir of weathered material compared with soils under short pasture or other non-forest vegetation. Much of this reservoir of weathered material is released when forests are converted to non-forest vegetation. "Short term" (in terms of geological time-scales) aggradation of riverbeds may result, but note we are not able to quantify what "short-term" really means.*

This process of "short-term" aggradation can be reversed by reforesting eroding areas currently under non-forest vegetation. Reforestation however is no guarantee against the consequences of extreme storm events where detritus from severe landslide and gully erosion may temporarily overwhelm a catchment's ability to transport sediment, regardless of the vegetation cover in the catchment."

Thus, even an intact tall forest cover does not offer protection against debris flows occurring over the "long-term" (although note the difficulty in defining "short-term and "long-term" in terms of decades, centuries or even millennia.)

Figure 10. Landslides and a debris flow on steep slopes with regenerating forest. Marlborough Sounds, July 2021. Note that despite the small size of the feature and its narrow track, the volume and velocity of debris was potentially destructive. (Marlborough District Council).

This is relevant to the current study because it has identified debris flow susceptible catchments in tall woody vegetation, with vulnerable built and natural environments in the downslope discharge zone.

While average return intervals for debris flows in such forested catchments may be extremely long (“a few times per century or even millennium” (Welsh and Davies 2010)), their impacts are serious and potentially life-threatening. This study is the first step towards identifying both forested and non-forested areas within the study area that are more susceptible to debris flows and floods. This will allow identification of potentially vulnerable receiving environments, buildings and infrastructure.

6. Use Cases

The results of this analysis are expected to be used under several different use cases. These could include (but are not restricted to):

1. Identification of potential debris flow susceptibility for new subdivisions. As development expands into new areas, developers will now have available a screening tool to help understand the potential need to perform further analysis around debris flow risks. This will help to better site dwellings or where to install mitigation devices.
2. Forestry management can objectively identify and manage catchments that might produce debris flows. Improved management practices such as retaining buffer zones, staggered harvests and appropriately sited earthworks can then help to reduce debris flow risk.
3. With further analysis, the screening layer can identify locations where significant infrastructure may be at risk of damage from debris flows e.g. properties, roads, power or water supplies, communication links etc. Once identified, action can thus be taken to reduce those risks.

7. Conclusions

1. This report seeks to classify sub-catchments within the study area as susceptible to debris flow or debris floods, with the limitation of little or no evidence from previous events.
2. Using newly-developed methods, we have been able to produce maps depicting Melton ratio and other catchment characteristics, down to small (0.5ha) sub-catchment scales over a large area of 344,873 ha.
3. These maps identify indicative debris flow and debris flood susceptibility in the study area's catchments. In some cases, interpretation is straightforward. In others, while susceptibility of sub-catchments is identified, there needs to be further work to estimate downstream runout distances of debris flows and floods.
4. The maps show debris flow and debris flood susceptibility, but not hazard, which requires an estimated likelihood or frequency of occurrence (return interval) and an understanding of catchment landslide susceptibility. Estimating the debris flow or debris flood runout "footprint" is also needed to fully characterise hazards. Debris flow and debris flood risk management will require further work on these aspects.
5. The methods used in this report can map sub-catchments down to less than 0.5 ha, but the ability of such small areas to generate debris flows is not clear. However, there is evidence that catchments down to ~10 ha in size can produce significant debris flows and debris floods, capable of endangering property and human health and safety. Many small properties are situated in the downslope discharge zone of debris-flow susceptible catchments in the study area. Therefore the hazard posed by small steep catchments needs careful investigation.
6. While steep catchments with a complete cover of tall woody vegetation have longer average return intervals between landslide events, they may still be susceptible to debris flows. These steep forested catchments need to be included in any debris flow risk management for the study area.

8. Future Work

Future work is recommended to improve the accuracy and usability of this debris flow susceptibility layer as a tool for management of debris flow risks. This work should include:

1. Determination of land use types in catchments. Understanding which catchments have high Melton ratios and land uses that increase catchment landslide susceptibility will help to determine downslope risk.
2. Further development of our understanding of debris-flow runout distances on fans, especially for large catchments
3. Improve understanding of the capability of small catchments to generate debris flows.
4. Refine understanding of sediment availability for mobilisation as debris flows.
5. Incorporation of built and natural environment layers into the debris flow susceptibility maps to help users view potential downslope receiving environments.
6. Correlation between documented historical debris flows in North Marlborough and the debris flow susceptibility layer. Has this layer adequately predicted sites with a history of producing debris flows?
7. Where the potential for significant debris flow hazards is indicated, institute a programme to develop evidence to test the debris flow susceptibility layer. This may involve further geoscience to identify evidence of previous debris flows at sites with potential for significant debris flow hazards.
8. Publication of the debris flow susceptibility layer for public information. The layer should be published with the clear understanding that it should only be used as an indicative screening layer. Where the layer suggests the potential for significant debris flow hazards, further expert geoscience advice should be sought.

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Appendix E-1. Map deliverables

Marlborough deliverables were compiled and delivered at the end of January 2022 to MDC. The deliverables contain a geodatabase (Marlb_BCG.gdb) with twenty segment Melton ratio rasters representing debris flows, and floods for their watersheds (See Figure 6 for locations). The geodatabase also contains the Melton ratio values assigned to the stream networks (streams and rivers) for each watershed. A folder called Marlb_KMZ_BCG contains the same stream network data, only in a KMZ format for the easy use and representation in the Google Maps environment. Supplementary data like elevation (DEM), and hillshade (topographic shading to provide the effect of depth) are also provided for graphic development in ArcGIS software. Marlb_BCG.mxd is provided with connections to all of the deliverable data. Once the deliverables are downloaded to the MDC system, the data can be viewed in ArcGIS software using by doubling clicking the Marlb_BCG.mxd icon. To open the kmz files, download Google Earth Pro and either double click the kmz file, or in Google Earth use the “open” icon to import the watershed file.