Preliminary estimation of catchment capacity to develop debris flows and their runout distances using high resolution Digital Elevation Models (DEMs)

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Abstract

Given recent occurrences of debris flow landslides from harvested forests in New Zealand, it is important to investigate the likelihood of debris flows from these sites. In this study, we examine simple methods for 1) identifying catchments where debris flows can initiate, and for those catchments 2) estimating the length of the debris flow runout zone. To do this, we use Ligar Bay (located on the north coast of the South Island, New Zealand) as a study area. In December 2011, Ligar Bay was subjected to a severe rainfall event, which led to devastating debris flows and associated debris floods. The effects of these debris flows were documented by GNS Science and their report is compared with the results of our analysis.

Introduction

A debris flow is a type of landslide that includes a combination of loose soil, rock, organic matter, air and water, all of which are mobilised and transported as a rapidly-moving slurry. On forestry clearfell sites, debris flows can mobilise not only rocks and soil, but also slash (harvesting residue) on slopes and in channels. These materials can 'run out' for long distances onto lowland environments, including river flood plains and the coast, where they end up on beaches (Phillips et al., 2016).

Through inundation and/or direct impact, debris flows can be a risk to both built and natural environments, as well as potentially causing injuries and loss of human life. Given the risks of debris flows from harvested forest sites it is important to investigate the likelihood of debris flows from these sites. In this study we examine 'desktop' methods for identifying catchments where debris flows can initiate, and for those catchments estimating the length of the runout of the debris flow.

To do this, we use Ligar Bay (located on the north coast of the South Island, New Zealand) as a study area. In December 2011, Ligar Bay was subjected to a severe rainfall event, which led to several devastating debris flows and associated debris floods. The effects of these debris flows were documented by GNS Science (Page et al., 2012) and their report provides a good baseline with which to compare the results of our analysis.

Background

Debris flows require a sufficiently large source of material (landslide debris), a source of water to saturate that debris, and a flow path that is steep enough to sustain the flow of saturated debris material (Kailey, 2013). Debris flow occurrence is therefore related to frequency and severity of landslides, which can be increased by predisposing factors such as deforestation.

The role of deforestation has specific relevance to New Zealand plantation forests, where forest canopy cover is completely removed by clearfelling on a 30-year cycle, as part of normal forest management. As a consequence, during the period after harvest when forest canopies and roots no longer provide protection from landslides, their occurrence increases substantially.

Debris floods ('hyperconcentrated flows') can also occur during debris flow events, or in other storm events where debris flows do not occur. Both debris flows and debris floods differ from normal flood flows in streams by having very high concentrations of suspended fine sediment (approximately 30% by weight; Davies, 1988), but only debris flows carry large boulders (Welsh & Davies, 2010). Peak flow rates of debris flows can be up to 50 times greater than ordinary flood flows (Page et al., 2012) because debris flows travel in surges, whereas debris floods do not surge but have peak flows two times greater than floods under equivalent conditions. These greater peak flows, and the much higher density of the debris flows/floods compared with ordinary floods, makes them more hazardous than ordinary floods under the same conditions.

Relevance of debris flows to NZ plantation forestry

Plantation forestry is an extensive land use, which profitably utilises land with limitations to agriculture in

A small debris flow originating from a clearfelling site in the Marlborough Sounds. Note that the debris flow has been able to transport debris originating from a mid-slope landslide right down to the coast and into the sea. Photo courtesy of Steve Urlich

terms of productivity, soil properties and topography. An important category of such limitations is soil erosion, and about 25% of New Zealand plantation forests are located on land that is highly susceptible to erosion.

For most of the forest rotation, the plantation forest mitigates landsliding on highly erosion-susceptible land, but after clearfell harvesting storm-triggered, post-harvest shallow landslides are likely to occur on such erosion-susceptible land. Where three factors (sufficient landslide debris, a source of water to saturate the debris, and a steep flow path) permit, debris flows may occur.

It is therefore essential for sustainable management of New Zealand plantation forests to identify catchments from which debris flows can initiate. In this study, we examine 'desktop' methods for identifying such catchments and estimating the potential length of the debris flow runout zone. This will allow forest managers and regulatory authorities to identify downslope fans and alluvial/coastal areas that are vulnerable to debris flows and floods.

Methods

Ideally, debris flow hazard would be inferred from detailed geomorphological data, coupled with mathematical modelling (Davies & McSaveney, 2008). However, this approach is costly in terms of time and money. In New Zealand, this cost precludes the wide use of such a detailed approach to investigating potential debris flow hazards in plantation forests.

Alternatively, the first step is to decide whether a specific catchment has the potential to initiate debris flows, but if it does not then no costly detailed investigations are needed. Where a catchment is identified as potentially able to initiate debris flows, the second step is to estimate 'runout' (i.e. how far a debris flow would travel downslope or downstream from the catchment). If the debris flow can travel beyond the steepland catchment where it originates and inundate lowland environments, then there is a clear need for more detailed investigations of the debris flow hazard. This is particularly so where high-value environments and/or human safety may be impacted.

Here we describe two simple methods for 1) estimating catchment capacity for debris flow initiation and 2) estimating debris flow runout distance. Rather than using detailed data or complex models, our methods are based on analysis of a Digital Elevation Model (DEM) using a Geographical Information System (GIS). The use of GIS means that catchments can be rapidly and cheaply classified on a desktop basis using existing DEMs.

Estimating catchment capability for debris flow initiation

Davies and Welsh (2010) developed a method for routine preliminary identification of potential debris flow catchments in New Zealand. The method uses the Melton ratio (R) and watershed length (WL) defined as:

> $R = H_b/A_b^{0.5}$, where H_b is catchment relief (maximum minus minimum altitude in the catchment) and Ab is catchment area (Melton, 1965)
>
> WL is the straight line distance between the points of maximum and minimum altitude in the catchment based on the model proposed by Wilford et al. (2004).

R and WL are indices of catchment steepness and size, two of the key factors identified by Welsh and Davies (2010) as predisposing debris flow occurrence. They classified Melton ratio values as follows:

$R \leq 0.30$	– the threshold below which conventional fluvial processes are generally dominant in a watershed
$0.30 < R < 0.60$	– the range for watersheds that are prone to debris floods
$R \geq 0.60$	– the threshold above which watersheds are prone to debris flows.

In addition, threshold classes were also defined for values of WL following Wilford et al. (2004):

WL≤2.7 km	– debris flows can occur in the watershed
WL>2.7 km	– conventional fluvial processes and/or debris floods are the dominant processes in the watershed.

Both R and WL can be calculated from existing DEMs, thus providing adequate discrimination of catchments that have the capacity to develop debris flows.

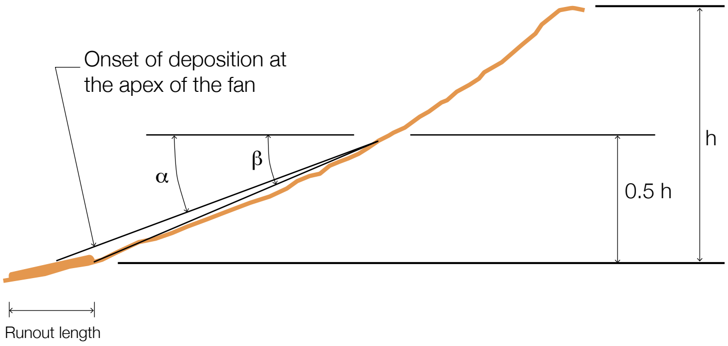

Figure 1: Angle of reach for a debris flow and its relationship to catchment profile. Source: Reprinted from Prochaska et al. (2008) with permission from Elsevier

Estimating debris flow runout distance onto fans

In this study, we used a simple method developed by Prochaska et al. (2008), which predicts the runout distance of a debris flow onto a fan, based on the angle (angle β in Figure 1) connecting the apex of a fan and the elevation half-way between this point and the drainage divide of the basin above it (= 0.5 h in Figure 1). The angle of reach (α) for the maximum extent of the debris flow runout beyond the fan apex was estimated as $\alpha = 0.88\beta$. A straight line projected downslope from 0.5 h at an angle α would intersect the fan surface at the point of maximum runout distance.

Although it seems simplistic, the method was tested and worked well for a variety of unobstructed, moderate-sized, non-volcanic debris flows in western North America over a range of ground covers and lithologies (Prochaska et al., 2008; Kailey, 2013). As with the Melton ratio, this method has the advantage that debris flow runout distances can be estimated directly from a DEM with no fieldwork or additional data requirements.

The study area

This study analysed debris flow occurrence and runout distances for a 1026 ha area between Tata Beach and Ligar Bay, northeast of Takaka township in the Tasman District (40° 49′ 13.3′′S 172° 55′ 18.5′′E) (Figure 2).

In December 2011, this study area was severely impacted by a high-intensity rainfall event that delivered 454 mm of rainfall over a 24-hour period (Page et al., 2012). The rainfall triggered severe landsliding and, in some catchments, debris flows and debris floods that caused about $10 million of property damage and posed a serious risk to human safety.

The upper catchments in the study area are underlain by Separation Point Granites (SPGs) (Page et al., 2012). SPGs are recognised as erodible and have a history of erosion and landsliding during high-intensity rainfall events, which occur frequently in Golden Bay and the adjoining Motueka Catchment.

The upper catchments in the study area comprise moderately steep (21–25°) and steep (26–35°) terrain. Altitude ranges from 20 m to 665 m above sea level (ASL). Below the steep hillslopes are gently sloping fans formed by the deposition of eroded sands, gravels and boulders transported from the steeper land upstream. These fans extend to the coastline over distances of 200–1000 m. The fans are traversed by a main public road and power reticulation. There are settlements scattered along the public road, and some parts of the fans have been developed for high-density housing.

After the December 2011 event, a detailed survey was made by GNS Science of landslide and debris flows triggered by the event, as well as the impacts on the downslope environment (Page et al., 2012). According to the GNS Science report, debris flows and/or debris floods occurred in eight catchments. However, in only three catchments did debris flows extend well beyond the apex of the upper fans and therefore pose a risk to human life and property downslope.

Geospatial analysis

In this study, Melton ratios and debris flow runouts were calculated for each catchment using a GIS to extract catchment morphological metrics from a DEM representing catchment terrain. Two DEMs were available from the LINZ Data Service:

- A 1 m cell size resolution DEM was accessed from the Tasman-Abel Tasman and Golden Bay LiDAR (Light Detection And Ranging) 1 m DEM (2016) – https://data.linz.govt.nz/layer/95578-tasman-abel-tasman-and-golden-bay-lidar-1m-dem-2016/

  LiDAR was captured for Tasman District Council by AAM New Zealand in December 2016. The datasets were generated by AAM New Zealand and their subcontractors.

- A second 8 m cell size resolution DEM was accessed from the New Zealand 8 m DEM (2012) – https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/

  This 8 m DEM was originally created by Geographx (http://geographx.co.nz) and was primarily derived from January 2012 LINZ Topo50 20 m contours (https://data.linz.govt.nz/layer/768).

There are advantages and disadvantages to using either DEM. GIS analysis of a 1 m cell size resolution DEM is computationally heavy (slow), and 1 m cell size resolution data is not available nationally but must be created from specially commissioned aerial LiDAR surveys.

Conversely, the 8 m cell size resolution is available nationally and is computationally easier to work with. However, the 8 m cell size resolution DEM was developed from 20 m contours, and therefore may only be representing the landscape at that resolution and at the time that the contour maps were photogrammetrically surveyed.

The coarser 8 m cell size resolution may not be critical when analysing steep catchments where the absolute error in the vertical plane and accuracy in relative gradient (slope) are less important. Therefore, the use of the 8 m cell size resolution DEM might be adequate for calculating the Melton ratio (R) for the steep upper catchments. However, in this study we also sought to measure debris flow runout distances on low-angle fans, where small errors in the estimation of slope could result in large errors in estimated runout distance. It should also be noted that the LINZ Data Service cautions that this 8 m cell size layer is 'suitable for cartographic visualisation only. It was created by the interpolation of 20 m contours with post-processing and filtering. It is not suitable for terrain analysis.'

For this reason, the analysis was performed using the 1 m cell size resolution DEM over most of the study area. Because the 1 m raster did not completely cover the upper terrain across the study area, the 8 m resolution data was resampled and merged with the 1 m raster to complete a small area in the southwest of the study area. Using GIS analysis of the 1 m cell size resolution DEM, we calculated Melton ratios and debris flow runout distances for all catchments to compare with observed occurrence of debris flows and floods in the December 2011 event.

First, the DEM rasters were masked to the catchment areas of interest, and an algorithm used to fill sinks, depressions and pits, resulting in a hydrologically sound DEM (i.e. water flows across the landscape from cell to cell without impediment).

The second step of the watershed and fan model was to develop a hydrologically sound catchment for each watershed. Stream and river channels across the entire fan and watershed surface were developed using the flow direction and flow accumulation commands and by setting an upper catchment threshold beyond which the stream stops. The filled DEM and the 'watershed' command in ArcGIS were used to develop each of the catchments across the area of interest, resulting in 23 catchments.

The third step was to develop the fan apex locations. This was achieved by intersecting the stream channel, the watershed and the fan, to provide the location at which the watershed opens out to the fan along the stream channel flow path.

Finally, for each of the 1 m cells along the flow path, elevation and the Euclidean distance from the fan apex (developed during the watershed delineation) were extracted. This provides us with both the watershed and the fan metrics from which we can calculate the Melton ratio and the runout length (as shown in Figure 2).

The GIS analysis was done using a Python script, which automatically calculates the Melton ratio and runout distances for each watershed and then outputs the results to a .csv file format.

Results

Figure 2 shows the catchment boundaries within the study area, delineated using the GIS analysis.

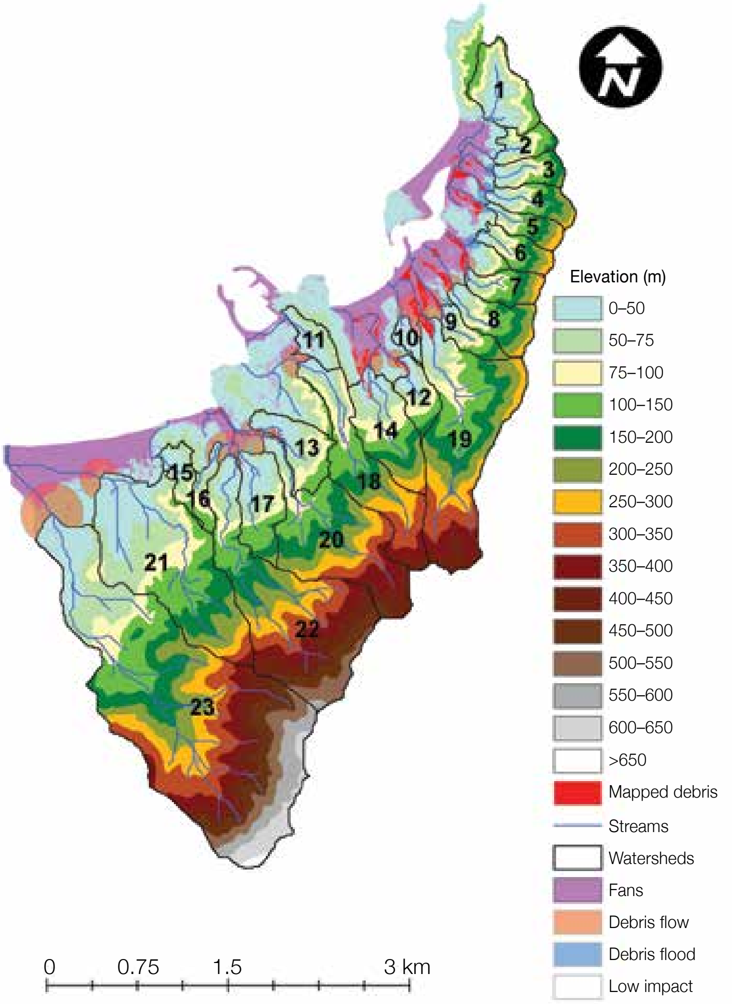

Figure 2: Catchment boundaries and mapped and estimated debris flow runout zones for the study area

Catchment sizes varied from small catchments (Catchments 1–17, areas ranging from 5–38 ha) in the northern end of the study area, to larger catchments in the southern end (Catchments 18–23, areas ranging from 56–276 ha).

Figure 2 also shows estimated debris flow runout distance for each catchment as the radius of a brown semi-circular arc from the fan apex. The GNS Science-mapped extent of debris deposition (debris flows and debris floods) is marked in bright red. Deposition in Catchments 1–9 resulted from debris floods. Debris flow/flood deposition in Catchment 19, which had the most significant impacts, is clearly shown.

Table 1 summarises catchment characteristics for the study area. Estimated Melton ratio (R) and runout distance were calculated using the methods described in this paper. The right-hand column shows the actual occurrence of debris flows ('Dflow') and debris floods ('Dflood') as reported by Page et al. (2012).

Discussion

While occurrences of debris flows and floods in 2011 were clearly related to R and WL, occurrence was not completely consistent with the thresholds proposed by Welsh and Davies (2010), as follows:

1. Welsh and Davies (2010) identify R>0.6 and 0.3<R<0.6 as thresholds for debris flow and debris flood occurrence, respectively. However, debris flows occurred at R~0.4 and above in the study area. In contrast, debris floods did not occur for catchments in the range 0.3<R<0.6, but were identified only in steeper but smaller catchments, with R = 0.6–0.77.
2. Wilford et al. (2004) and Welsh and Davies (2010) state that debris flows are unlikely in catchments longer than 2.7 km, although there are examples of longer catchments that have generated debris flows (e.g. Illgraben DF research catchment in Switzerland is 4.5 km long). In this study, most of the catchments were smaller than 2.7 km, but one of them (Catchment 23) was 3.38 km in length yet generated a significant debris flow in 2011.
3. At the same time, small catchments (<1,000 m in length and <30 ha in area) showed a distinct break at R = 0.5, with no debris flows or debris floods occurring below this threshold. This is not to say that these catchments are not capable of generating debris flows or floods. For debris flows and floods to occur, there needs to be a minimum volume of landslide debris. It may be that in the 2011 event, landslide volume was insufficient to generate debris flows in these smaller catchments, even though the catchment morphology (R) would have allowed a flow to initiate, given a sufficiently large volume of debris.
4. Also of interest was the occurrence of debris floods where R>0.6. One possible explanation is that these debris floods were associated with debris flows, but these were small and did not run out onto a downslope fan. Therefore, evidence that debris flows occurred may have been missed, since the associated debris floods would have reached further downstream.

Estimating runout distance

Unfortunately, specific runout distances for debris flow catchments were not mapped by GNS Science. Thus, it was not possible to compare estimated runout distances using the Prochaska method with observed runout distances.

However, catchments were classified into those where debris flows and/or debris floods occurred and those where none occurred. Those catchments that had debris flows in 2011 also had markedly longer estimated debris flow runout distances, while those that had debris floods had very small estimated runout distances. Interestingly, while most catchments that had no debris flows or debris floods had relatively low values for estimated runout, there were a few with estimated runout distances greater than 50 m – a longer distance than estimated for the catchments that generated debris floods. This reinforces the earlier point that smaller catchments did not generate debris flows or floods, even though they were steep enough to do so. Thus, the observed lack of debris flows and floods in one event (2011) may not reflect the potential of small catchments to periodically generate debris flows.

Assessment of debris flow hazard

Page et al. (2012) assess the annual exceedance probability of at least one debris flow occurring downslope of the study area as 0.5% or 10% over 20 years and describe this as ‘unacceptably high.’ An approximate hierarchy of catchments for debris flow hazards was proposed (catchment numbers as in Figure 2):

- Most hazardous – Catchment 19
- Hazardous – Catchments 7, 8
- Least hazardous – Catchments 3–6, Catchment 9.

This hazard assessment can be compared with the R values and calculated runouts in this study. Catchment 19 is clearly hazardous. While its calculated R was only 0.4, its estimated runout distance is 200 m, extending well into an intensively developed fan.

Table 1: Catchment characteristics for the study area

Catchment no.	Area (ha)	WL (m)	Max. elevation (m)	R	Estimated runout (m)	Dflow/ Dflood
1	27.1	700	151	0.27	53	None
2	10.8	575	180	0.50	70	None
3	12.8	604	233	0.60	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
9	11.7	792	282	0.77	59	Dflood
10	5.0	464	74	0.30	24	None
11	11.1	650	81	0.23	45	No data
12	14.3	761	224	0.54	66	Dflow
13	22.6	728	155	0.29	79	None
14	38.2	1200	327	0.50	104	Dflow
15	10.4	712	129	0.37	85	None
16	8.1	740	129	0.41	35	None
17	28.6	1003	244	0.42	103	None
18	56.0	2005	425	0.53	126	Dflow
19	103.4	2175	425	0.40	200	Dflow
20	79.6	1907	484	0.52	157	Dflow
21	111.8	2021	426	0.39	160	Dflow
22	118.7	2271	567	0.50	177	Dflow
23	276.4	3385	665	0.39	249	Dflow

The hazards associated with Catchments 3–9 are less clear. While all catchments have a high R (0.6–0.77), they are small and estimated runout distances are short (46–70 m). In December 2011, all these catchments developed debris floods rather than debris flows.

The hazards for the large catchments in the southern part of the study area (Catchments 12, 14, 17–23) appear to be far more significant. These large catchments do not have particularly high R values (0.39–0.54), but all except one developed debris flows in 2011. Because of the size of the catchments, estimated runout lengths from the fan apex range from 103–249 m. Although many of the fans below these catchments are not intensively developed, this study suggests a serious hazard to the built and natural environments within the estimated runout distances.

Effect of DEM resolution

The geospatial models for this study were developed using a high resolution 1 m DEM, as we saw a need for accuracy in estimating slopes and therefore runout distances on fans. The studies by Welsh and Davies (2010) and Prochaska et al. (2008) used spatial information at a coarser resolution. Welsh and Davies (2010) used a 25 m DEM to estimate R for their study catchments. Prochaska et al. (2008) used topographic maps ranging in scale from 1:24,000–1:50,000 to analyse the morphology of their study catchments. Further work is needed to compare the estimates of R and debris flow runouts for catchments gained from analysing high resolution versus coarse resolution DEMs.

Conclusions

The study area has been a useful location to evaluate catchment capacity to develop debris flows and estimate their runout distances. The results of the 2012 GNS Science study were a good baseline to compare with estimated Melton ratios and calculated runout distances. However, debris flow runouts were not mapped after the December 2011 event, so that estimated runout distances cannot be compared with observed values. To truly test the use of the Melton ratio and Prochaska method as a screening tool for catchments with debris flow hazards, they need to be tested using data from studies where runout distances of debris flows were measured.

The study confirmed the practicality of processing high resolution DEMs to automatically generate R, WL and debris flow runout estimates. Since these automated estimates were generally consistent with the findings of the 2012 GNS Science report it is worth continuing the development of these geospatial methods. As high resolution DEMs become available widely on a regional basis, it will be possible to identify potential debris flow hazards with much greater accuracy and generate region-wide maps of potential debris flow hazard. Such maps would allow forest managers and regulatory authorities to focus further detailed studies and management effort on the areas where debris flow risks are greatest.

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